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URS 639-4

STRUCTURAL DEBRIS CAUSED BY NUCLEAR BLAST

Research Report
October 1964

Prepared for

OFFICE OF CIVIL DEFENSE
Office of the Secretary of the Army
Department of the Army
Washington, D.C. 20310
Contract Number OCD-PS-64-19
Subtask 3312B

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ADDENDUM TO

SUMMARY REPORT URS 639-4

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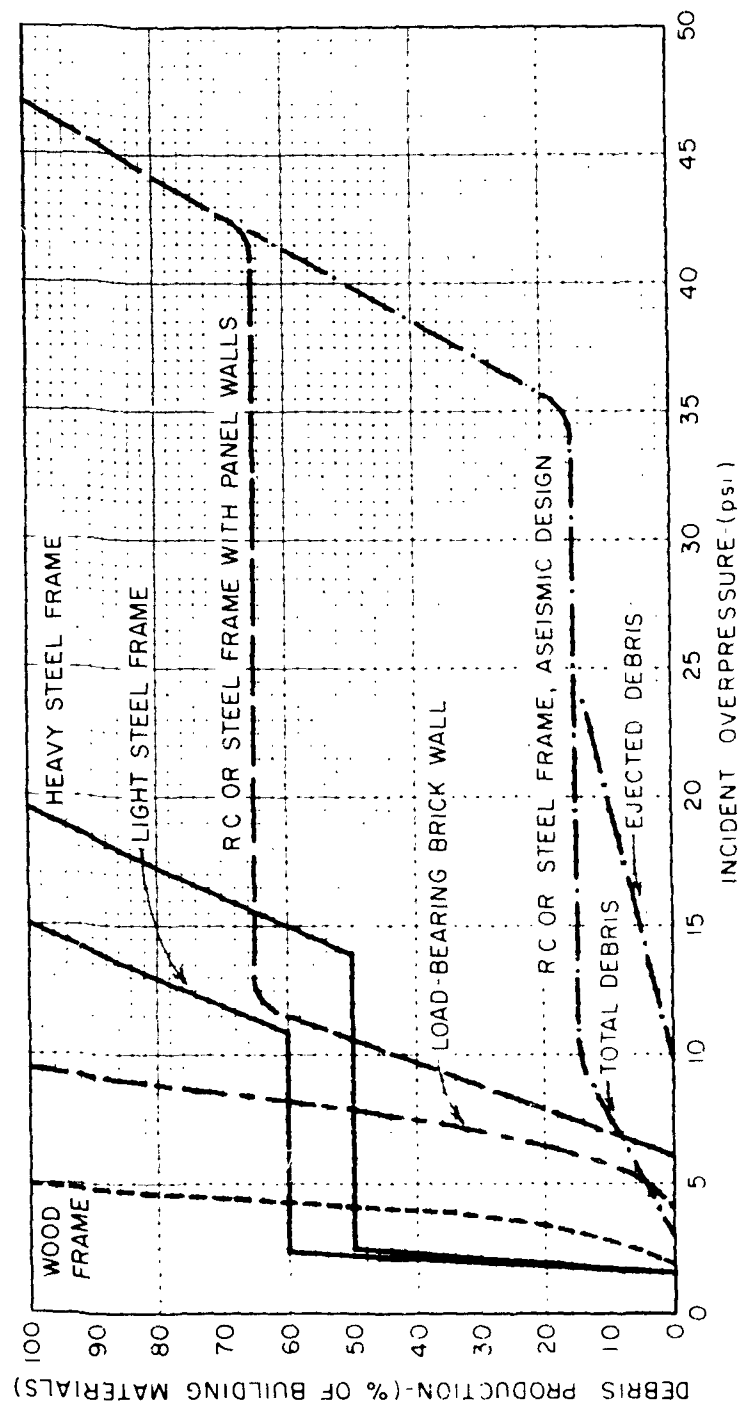

Figure 1. Debris Production vs. Overpressure; 20 Kiloton Weapon

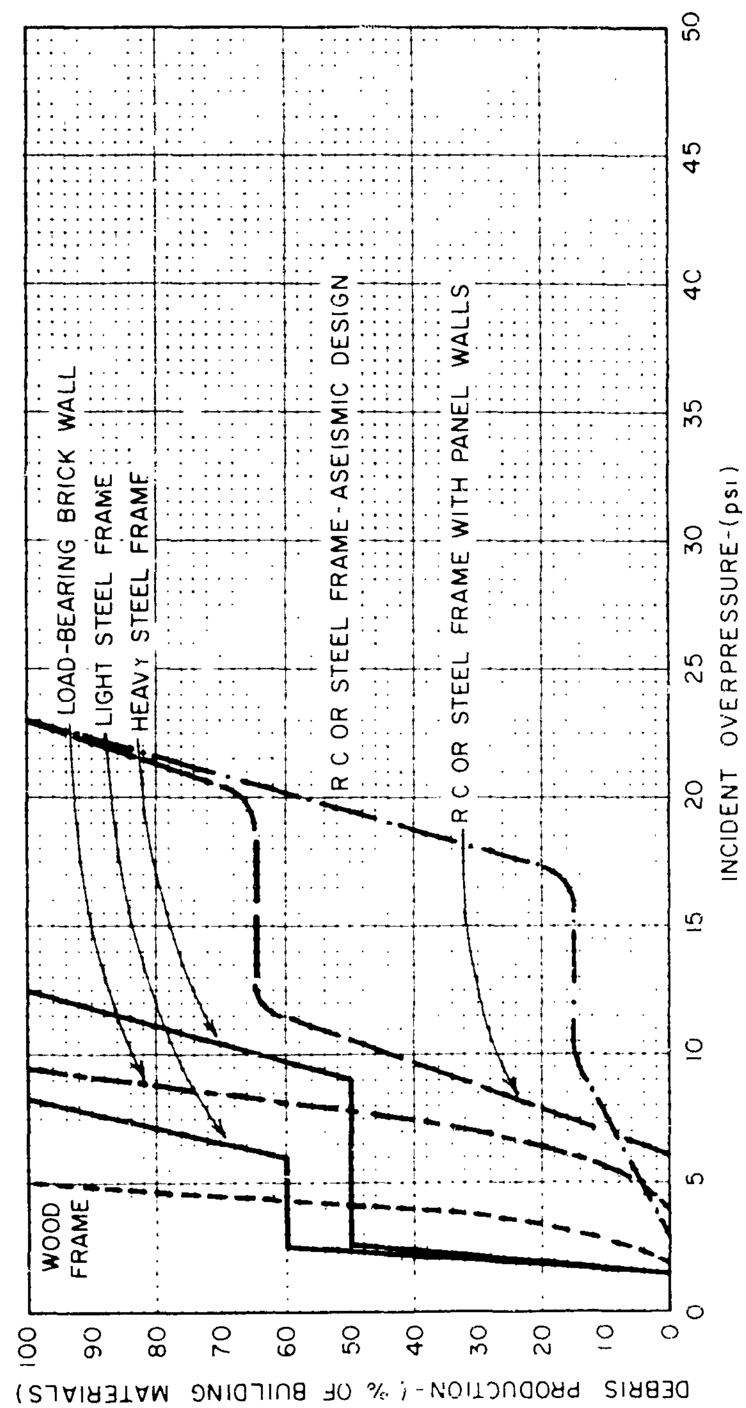

Figure 2. Debris Production vs. Overpressure; 20 Megaton Weapon

Summary Report
of

STRUCTURAL DEBRIS CAUSED BY NUCLEAR BLAST

Report No. 639-4

by

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NOTICE

This report has been reviewed in the Office of Civil Defense, Office of the Secretary of the Army, and approved for publication.

Summary Report
of

STRUCTURAL DEBRIS CAUSED BY NUCLEAR BLAST

The purpose of this program was to develop means for predicting the quantity of structural debris produced by air blast from various types of nuclear weapon attack. In order to provide as realistic estimates of debris quantities as possible, detailed analyses were made of reports of situations that resulted in the production of debris, in particular of the damage reports on the attacks on Hiroshima and Nagasaki and of the reports on those Nevada Test Site and Pacific nuclear weapons tests in which structural damage was observed.

In general it was not found possible to base quantitative estimates of debris on existing analyses of damage, since structural damage and the debris produced as a result of the damage are not necessarily related. Instead it was necessary, in all cases, to make new estimates of both the quantities of material contained in various elements of structures (roof, wall, floors, frame, etc.) and the portions of these materials that became debris.

Most of the applicable basic information was derived from tests (or attacks) with kiloton-range weapons, and therefore the first curves developed for estimating debris quantities--as functions of incident air blast overpressure level--were for kiloton-range weapons. However, analysis of the influence of the longer overpressure durations from megaton-range weapons on structural behavior permitted the development of curves predicting debris quantities for these weapons.

The results, to date, of the program are summarized in Figs. 1 and 2, which show debris quantities as a percentage of total building materials produced by various air blast overpressures from both kiloton- and megaton-range weapons for six classes of structures (light and heavy industrial, ordinary and aseismic design steel and reinforced concrete frame, wooden, and brick or masonry).

It is recommended that techniques be devised for estimating air-blast-caused debris for structures and classes of structures other than those named and for estimating the influence of fire on debris production; that studies of debris distribution be increased in scope; and that application of the techniques developed be made in a number of cities.

URS 639-4

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INTRODUCTION

BACKGROUND

Postattack recovery and reclamation operations are concerned, in part, with the production of debris by total or partial collapse of buildings and structures. This debris, until removed, can severely limit access to large areas of cities by any but the most primitive forms of transport and, similarly, can make normal access routes through these areas useless.

How this problem will be met in a particular situation, that is, whether debris will be removed and, if so, to what degree and with what effort, depends on many factors, not all relating to the debris itself. Thus, if debris has blocked a major access route through an area, consideration must be given to the need for reestablishing the particular route, the possibility of establishing alternate routes, the type of access needed (e.g., a one-lane as opposed to a multilane road), as well as to the quantity of debris that must be removed and the effort required to remove it. This study has addressed itself to only one facet of the problem, that of providing means for estimating the quantity of debris that would be produced by weapon attack*.

In an earlier study carried out by IIT Research Institute,[1]** many American buildings were analyzed to determine the total amount of material they contained (which would, of course,

---

*Other aspects of the problem, such as the logistics of debris removal, are currently being studied.

**Numbers refer to references listed at the end of the report.

determine the maximum amount of debris that could be produced upon total building collapse), and studies at that organization are continuing to develop mechanistic models of building failure.

In this study, by making use of information from actual events that created debris, URS has attempted to develop means for predicting debris quantities under attack conditions less severe than those that would result in total structural collapse. By this means, it was believed that techniques for estimating realistic debris quantities could be developed in a relatively short period of time.

GENERAL CONSIDERATIONS

Debris has been defined simply as the material contained in those portions of buildings or structures that have undergone complete failure due to air blast and, thus, impede access to or through an area. Perhaps the most critical part of the definition for this study is its last part, that the material must ". . . impede access to or through an area." When a structure is completely collapsed and its material uniformly distributed over a considerable area, whether or not a portion of the debris remains on the original building site is largely academic. In a sense one need not anticipate any more difficulty in going through the site itself than in going through what was originally a nearby street.

When, however, less than total collapse occurs, complications arise. Portions of structures may remain intact; rubble of failed elements can remain within the site; and, in certain cases, only a small portion of a large quantity of rubble can be found outside the original site. Because access through an area can be greatly affected by the distribution of debris, it would be desirable to distinguish, if possible, between debris that remains on an original building site and that which leaves it.

Note one additional important element of the definition: debris is the material from portions of the building that have collapsed completely. This removes from the debris category portions of building, such as frames and floors, that remain in place, whether or not they can carry out their intended function. This distinction was made because removal of such elements would require first that they be demolished, i.e., that they be reduced to debris.

Whether debris will be produced and, if so, of what type depends on the characteristics of the presumed attack and those of the target, i.e., the building.

In an air burst of a nuclear weapon, a sharp-fronted shock wave forms and moves radially out from the source. When this shock wave first encounters the ground surface, it undergoes regular reflection, in which only two shocks, the incident and the reflected waves joined at the ground surface, are involved. In regular reflection, the flow near the ground surface has a large vertical component. As the incident shock expands, it impinges on the ground at more glancing angles of incidence and, at some critical angle, Mach reflection begins. The reflected wave overtakes the incident; they intersect above the surface; and a third shock, the Mach stem, forms to join the rising intersection (the triple point) with the surface. Flow in the Mach stem near the surface is parallel to it. In a surface burst of a nuclear weapon only one shock forms (it can be thought to be a combination of incident and reflected waves) in which, as with the Mach stem, flow near the surface is parallel to it.

In general, when a sharp fronted shock wave moving parallel to the ground encounters a target or other object on the surface, it first reflects from the object, subjecting it to a load greater than the incident overpressure. The shock wave then diffracts around the object, subjecting it additionally to loading due to the movement of air particles in the shock wave, a type of loading that is measured by the so-called dynamic pressure, $1/2\ \rho u^2$, where ρ = density and u = particle velocity. Eventually, if the shock wave duration is long enough, it subjects the object to so-called drag phase loadings that are composed of the sum of the static overpressure in the shock wave plus a drag loading due to the shock wave dynamic overpressure. Diffraction phase loadings, i.e., those that occur during the time taken for the head of the shock wave to pass over the object, are usually higher* than those that occur during the drag phase, or than those that occur between the time for completion of diffraction phase loadings and the onset of drag phase loadings (the transition phase). The durations of diffraction and transition phase loadings are not greatly affected by the total duration of the shock wave, since they are related to the time for pressure signals to propagate from one part of a building to another. Duration of drag phase loading, on the other hand, depends directly on shock wave duration**.

From the above summary of phenomena, it can be seen that the characteristics of a nuclear weapon attack that enter into the production of debris are the direction of shock wave flow and, more particularly, whether regular reflection takes place or not, the incident shock wave overpressure, the dynamic pressure and the shock wave duration, or measures of weapon yield that are related to these parameters.

Target characteristics that should be considered for a rational analysis of the debris problem are far greater in number, and depend in part on the attack parameters themselves. Among the more obvious target characteristics of importance are the size and shape of the buildings, the material composing them, and their manner of failure.

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*For air bursts under certain conditions, thermal radiation from the burst of a nuclear weapon can cause a so-called precursor to form. Where this occurs, the shock wave will not, in general, be sharp fronted, dynamic pressures will be high, and the loading throughout the pulse can be approximated by the sum of incident static overpressure and dynamic pressure drag.

**Overpressure, dynamic pressure, and shock wave duration are all related to weapon size and distance from the point of explosion. For two weapons of yield Y_1 and Y_2, overpressure and dynamic pressures at distances R_1 and R_2 will be the same if $R_1/(Y_1)^{1/3} = R_2/(Y_2)^{1/3}$; duration at distance R_2 will equal duration at R_1 multiplied by $(Y_2/Y_1)^{1/3}$.

In a gross sense, entire buildings or their elements can be divided into two groups: those that fail due to rapidly applied diffraction phase loadings and those that fail only under longer time, transition, and drag-phase loadings. The most important characteristics of a target that determines the group in which it should be placed are its natural period relative to the shock wave loading duration, and its ability to retain useful load carrying characteristics after it has exceeded its elastic yield point (which is measured by ductility, the ratio between breaking strain and strain at the elastic yield point).

The distinction is useful (though greatly oversimplified) for it gives an immediate basis for choosing among categories of buildings or their elements. Those that are composed of "brittle" (nonductile) materials such as masonry, wood, etc., would naturally be grouped separately from those that have considerable ductility (steel frames, for example).

Among other target parameters that might be considered are those of building orientation, placement of buildings relative to each other (close placement can affect shock wave loadings), and building size (as measured, for example, by the number of floors).

In summary, a complete analysis of the debris problem should include consideration of the following:

- Attack Parameters
  - Incident overpressure
  - Shock wave duration
  - Dynamic pressure
  - Direction of incident flow (i.e., whether regular or Mach reflection occurs)
- Target Parameters
  - Building type, size, and orientation
  - Construction materials
  - Manner of failure
  - Relationship to other structures
- Debris Parameters
  - Amount
  - Distribution (on site and off site)
  - Type

SOURCES OF INFORMATION

A number of sources of information were considered in this study: the atomic bomb attacks on Hiroshima and Nagasaki; the controlled nuclear weapons test in Nevada and the Pacific; analyses of these tests and theoretical studies that lead to methods for estimating building damage; the large accidental explosions at South Amboy and Texas City; and reports on natural disasters (tornados, hurricanes, etc.). Natural disasters were eliminated quite early in the study when it became obvious that the dissimilarity in loading parameters would make the information from the natural occurrences difficult to interpret in terms of nuclear weapon parameters.

The events at South Amboy in 1950[2/] (in which approximately 60 tons of commercial explosives being loaded from freight cars to barges exploded) and at Texas City in 1947[3/] (in which close to 1000 tons of ammonium nitrate fertilizer in the hold of a vessel exploded, killing 512 persons and injuring 3000) were among the largest accidental explosions to take place near populous areas. Here too, however, it was found that the information on these disasters could not be readily interpreted in terms of nuclear weapon parameters, in part because of the large differences in size of explosion, in the case of the South Amboy disaster, and in part because of the type of data available (overpressure levels in both cases were difficult to determine; the Texas City disaster involved two separate large explosions; and the structures that did produce debris there were poorly documented).

Thus the only sources used in this study were information on the attacks on Hiroshima and Nagasaki, the Nevada and Pacific nuclear weapons tests, and collateral analyses of these data and theoretical studies. Brief descriptions of these sources are given below.

Hiroshima and Nagasaki Data[4-9/]

On August 6, 1945 a fission bomb whose estimated yield was 13 kilotons was exploded approximately 2000 feet above Hiroshima; and on August 9, 1945 a similar weapon with a yield of 22 kilotons was exploded some 1600 feet over Nagasaki.

Hiroshima, a light industry, communications, and military center with a population of about 245,000 on the attack date, suffered moderately severe building damage over an area of 9.5 square miles. Approximately 60,000 to 90,000 buildings were totally or severely damaged. Nagasaki, a heavy industry center ringed partially by mountainous terrain, suffered severe damage over an area of 1.8 square miles. (Nagasaki's built-up area was only about 3.3 square miles.)

In October and November 1945, two teams from the Physical Damage Division of the U.S. Strategic Bombing Survey (USSBS) conducted surveys in the cities which included field inspections, gathering of statistical and documentary information, and numerous interrogations and interviews. At Hiroshima[4,5,6], 173 individual buildings were surveyed and reports on most of them contain information on building floor plans, construction materials, amount and type of damage including fire damage, and, finally, ground photographs from several vantage points.

At Nagasaki[7,8,9], a greater number of individual buildings were surveyed, and for each, information similar to that reported for Hiroshima was given, except that many fewer floor plans and building sketches, and many fewer ground photographs were given. For this study, detailed structural information was required and, therefore, the information from Nagasaki, while more voluminous than that from Hiroshima, was less useful.

Nuclear Weapon Tests

In the period 1947-1963, several nuclear weapons tests designed specifically to develop information on damage to structures were conducted. These included tests at the Nevada Test Site in which a large amount of information concerning both residential and industrial steel frame structures and their elements (such as wall panels) was obtained. The weapons were in the kiloton range.

Operation Upshot-Knothole[10-13], in 1953, included tests of wood frame houses, and panel walls and partitions of various materials. Operation Teapot[14-16], in 1955, retested wood frame houses. Other house types included in this test were brick, one-story precast concrete, and one-story concrete block. Operation Teapot also tested steel frame industrial buildings and self-framing industrial buildings.

Operation Plumbbob[17], in 1957, retested some of the aforementioned structures.

These tests were described in reports that gave a very thorough presentation of the data. In general, the tests were set up with the structure or structural element to be tested located at two different ranges from ground zero, selected so that one building would be destroyed, and the other would remain standing. Photographic coverage was excellent, consisting of before and after pictures. It was not difficult to extract useful information from these test reports.

Data from the Pacific tests were reported in the same manner as those from Nevada; however, many structures tested were not typical of structures in cities, being massive and nonresponding. This was unfortunate, as many of the weapons used had megaton yields.

Operation Greenhouse[18-25], in 1951, was the first test in the Pacific from which usable data could be obtained. It included a two-story brick-row apartment building, a three-story structure composed of seven separate buildings of varying construction, and other buildings which provided quantitative information.

The only other test series in which useful information was developed was Operation Redwing[26] in 1956.

Collateral Sources

Although the bombings of Japan and the nuclear weapon tests described above represent the only physical data sources, a number of analyses of these data and theoretical analyses of structural response have been made over the years for the purpose of estimating damage to buildings (not debris). These (for example, reference 27) have led to the development of damage-production criteria that appear in references 28 and 29. Information contained in these and similar sources, although not directly applicable to the debris problem, has been used to aid in constructing debris production curves where directly useful data were not available.

Chapter 2

ANALYSIS

DATA REDUCTION

The objective of the data reduction portion of the program was to determine--to the degree of accuracy that the available data permitted--the quantities of debris produced by blast for as many different structures as possible. This proved to be a tedious, time consuming task, for it soon became apparent that it was necessary to analyze each structure in considerable detail. Each structural element, i.e., roof, exterior walls, framing, interior partitions, and floors, had to be given separate consideration, and estimates had to be made of the quantities of material contained in each and of the portions that failed.

A sample of the data reduction sheet used in analyzing the nuclear weapon data is shown in figure 1. Three entries on the figure require some explanation: "Total that is combustible" reflects the fact that in later phases of this study, attempts will be made to determine the effect of thermal radiation and fire spread on the debris picture; "By IITRI method _% of total volume . . ." refers to a method given in reference 1 for computing the total quantity of material contained in certain building types (the Hiroshima and Nagasaki information afforded opportunity to compare the results of this method with computations of material volumes for actual structures); "Total material that is off-site debris" reflects the fact that, in general, only the debris that does not remain on a building site would affect access to the structure or through the area. As will be seen, not all the available data allowed determination of that portion of total debris produced not remaining on site.

Hiroshima Data

An example of the typical level of information detail on a building in Hiroshima is shown in figures 2, 3, and 4. The completed original URS data reduction sheet for that structure is shown in figure 5.

________ CALCULATIONS

MATERIAL QUANTITIES

a) Roof

b) Exterior Walls

c) Framing

d) Interior partitions

e) Floors

a)	cu. ft.
b)	"
c)	"
d)	"
e)	"
Total	cu. ft.

Total that is combustible = ________ = %

By IITRI method % of total volume contained in building

cu. ft.

DEBRIS QUANTITIES

a) Roof

b) Exterior walls

c) Framing

d) Interior partitions

e) Floors

a)	cu. ft.
b)	"
c)	"
d)	"
e)	"
Total	cu. ft.

Total material that is offsite debris = ________ = %

Total offsite debris that is combustible = _____ = %

REMARKS

Figure 1. Sample of URS Data Reduction Sheet

U. S. STRATEGIC BOMBING SURVEY

PHYSICAL DAMAGE DIVISION

Field Team No. 1, Hiroshima, Japan

BUILDING ANALYSIS

SHEET No. 1

Building No.: 84. Coordinates: 4G. Distance from (GZ): 3,300, (AZ): 3,900.
NAME: Okita Iron Works.
CONSTRUCTION AND DESIGN
Type: Light steel trusses, brick-bearing walls.
Number of stories: 1. JTG class: A 2-3.
Roof: Asbestos shingles on wood sheathing and purlins.
Partitions: None.
Walls: 13-inch brick.
Floors: Concrete on earth.
Framing: Roof only—steel trusses.
Window and door frames: Wood. Ceilings: None.
Condition, workmanship, and materials: Good.
Compare with usual United States buildings: Comparable.
OCCUPANCY: Light machine shop.
CONTENTS: Machine tools and stock.
DAMAGE to building: All walls completely leveled, dropping trusses to ground, rupturing and buckling them. Slight amount of debris damage by fire.
Cause: Blast.
To contents: Machine tools and equipment severely damaged by fire with some additional exposure damage. Slight amount of debris damage.
Cause: Fire (50 percent). Exposure (20 percent). Debris (10 percent).
TOTAL FLOOR AREA (square feet): 7,000. Structural damage; 7,000. Superficial damage:
FRACTION OF DAMAGE: Building structural: 100 percent. Superficial: —. Contents: 80 percent.
REMARKS:

NOTE.—Building damage based on total floor area. Contents damage is fraction of contents seriously damaged.

SHEET No. 2

(Fire Supplement to Sheet No. 1)

Building No.: 84. Fire classification: C.
WALL OPENINGS: Shutters: None.
Shut:
Effect of blast:
FLOOR OPENINGS:

	Enclosed	Fire doors	Automatic	Effect of blast
Stairs:				
Elevators:				

EXPOSURE.

Location	Distance	Firebreak Clearance	Class	Fire Burned	Remarks
N	40'	No	C	Yes	
E	25'	No	C	Yes	
S	25'	No	C	Yes	
W	0'	No	C	Yes	

PROBABLE CAUSE OF FIRE: Not determined.
VERTICAL FIRE SPREAD:
EXTENT OF FIRE: Total floor area: 7,000 square feet. Floor area burned: 7,000 square feet; 100 percent (after blast damage).
REMARKS:

Figure 2. Typical USSBS Hiroshima Building Analysis Sheet

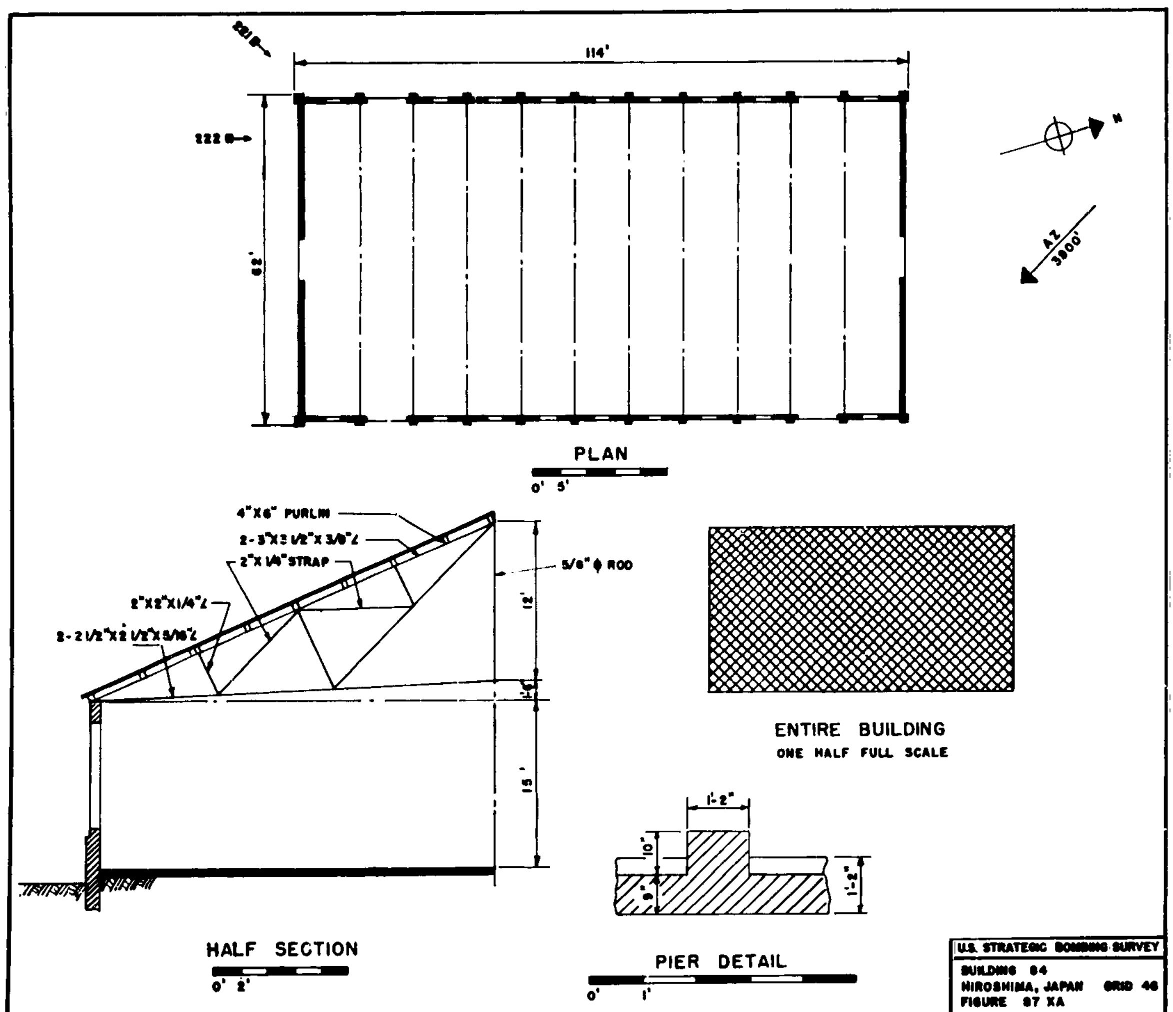


Figure 3. Typical USSBS Hiroshima Building Construction Details

Building 84. General view looking northeast, showing complete collapse of building by blast. Combustible roof debris and contents burned. Building No. 83 is in right background.

Building 84. Looking north along axis of building, showing complete collapse of walls and trusses by blast.

Figure 4. Typical USSBS Hiroshima Postattack Photographs

Hiroshima CALCULATIONS *Building 84*

MATERIAL QUANTITIES

a) Roof $(\frac{1/4}{12})(114)(68) + (\frac{1}{12})(114)(68) + (\frac{4 \times 6}{144})(114)(18) = 160 + 645 + 342$
$= 1147$

b) Exterior walls $(\frac{9}{12})(114+62)(2)(15) + (\frac{14 \times 10}{144})(15)(24) + (\frac{5}{12})(114+62)(2)(3)$
$-(24)(18)(\frac{9}{12}) - (56)(6)(\frac{9}{12}) = 3955 + 350 + 440 - 324 - 252 = 4169$

c) Framing - *for one bay*
$(60)(2)(\frac{1.47}{144}) + (60)(\frac{0.94}{144}) + (34)(\frac{2 \times 1/4}{144}) + (68)(2)(\frac{2.3}{144}) = 1.22 + 0.4 + 0.12 + 2.18$
$= 3.92$

d) Interior partitions $3.92 \times 10 = 39$
-0-

e) Floors
-0-

a)	1150	cu. ft.
b)	4170	"
c)	40	"
d)		"
e)		"
Total	5360	cu. ft.

Total that is combustible $= \frac{645+342}{5360} = 18$ %

By IITRI method 11 % of total volume contained in building

$V = (62)(114)(19)(0.11) = 14,772$

14,770 cu. ft.

DEBRIS QUANTITIES

a) Roof $90\% = (0.9)(160+645) = 724$

b) Exterior walls
$60\% = (0.6)(4170) = 2502$

c) Framing
-0-

d) Interior partitions
-0-

e) Floors
-0-

a)	720	cu ft.
b)	2500	"
c)		"
d)		"
e)		"
Total	3220	cu. ft

Total material that is offsite debris $\frac{3220}{5360} = 60$ %

Total offsite debris that is combustible $\frac{390}{3220} = 12$ %

REMARKS

Total debris = 100%

Figure 5. Original URS Data Reduction Sheet for Building Described in Figures 2, 3, 4

The manner in which the Hiroshima data were presented made them extremely useful for the study. The drawings and building analysis sheets were detailed enough that material volumes could be calculated with a good deal of accuracy. In general, the ground photography was complete enough that estimates could be made of both the total amount of debris produced and of the amount that remained on the original building site.

Special Considerations

Examination of the typical survey sheets reveals some of the specific problems of interpretation that arose while using the Hiroshima data. They describe damage in general terms and then report what portions of the damage were "structural" or "superficial." Structural damage was defined as damage to principal load-carrying members (trusses, beams, columns, load-bearing walls, floor slabs in multistory buildings) requiring replacement or external support during repairs. Light members such as purlins and rafters were not included. Superficial damage was damage to purlins and other light members and stripping of roofing and non-load-bearing exterior walls but did not include damage to glass and interior partitions.

Unfortunately, neither of these damage categories necessarily yielded information on the debris produced by a building. For example, if a roof was depressed in a two-story reinforced concrete building, but there was no other damage, the building would be said to have 50-percent structural damage and 0 percent superficial damage, but the only actual debris from the building would be the portions of interior partitions that failed.

In such cases, and indeed in all cases, casual use of the survey information was not possible. For each building, it was necessary to carefully examine the photography and analyze the survey information before debris estimates could be made.

Before leaving this description of the Hiroshima information, it might be worth noting that the Hiroshima reports included comprehensive summaries of the data, including graphs and tables, of damage to the various categories of buildings from fire and blast and the variation of the damage with range. In reading this report, one gained considerable insight into Japanese construction and the damage caused by the atomic bomb.

Nagasaki Data

Building analysis sheets for Nagasaki, though arranged differently from the Hiroshima sheets, generally contained the same information. Unfortunately for this study, however, most sheets were not accompanied by drawings, which made it impossible to calculate debris quantities. An example of a building analysis is shown in figure 6, and on figures 7, 8, and 9 are shown the supporting photographs, construction details, and the original URS data reduction sheet for the building.

Note that neither data reduction sheet has an entry for off-site debris. Such estimates for Hiroshima buildings were made by carefully examining ground photography, which, because it generally showed the building site from two to three different directions, allowed estimates to be made of the material that remained on the building site (and thus of the material that was no longer on site) with some confidence. Nagasaki photography, on the other hand, was not nearly so complete, often showing only one aspect of the building and then not clearly identifying the direction from which it was taken. After a few attempts were made to estimate off-site debris, it was concluded that these estimates were not valid and, therefore, these attempts were abandoned for the Nagasaki data.

Special Considerations

As with Hiroshima data, Nagasaki survey data required careful interpretation. Thus, although structural damage is given in terms of the degree of damage (in percent) to structural elements, great care was required to convert these measures of damage to measures of debris.

DAMAGE ANALYSIS

Dimensions: 300 by 87 feet.
Ground floor area: 26,100 square feet.
Total area: 26,100 square feet.
Number of floors: 1.
Eave height: 16 feet.
Mean elevation: 15 feet.

Group 4.
Building No. 10.
Occupancy: Machine shop.
Building type: Light steel frame (B2).
Fire classification: N.
Ground zero: 4,600 feet.

Construction	Damage			Description of damage
	Structural (percent)	Superficial (percent)	Cause	
Roof: Corrugated asbestos	0	100	Fire and blast.	Entire building blown north.
Trusses: Steel	100	0	do	
Columns: Steel	95	0	do	
First floor: Concrete	0	0		
Foundation: Concrete	5	0	Fire and blast.	
Exterior walls: Corrugated asbestos	0	100	do	
Windows: Steel sash	0	100	do	
Contents: Machine tools and cranes	0	0		

Figure 6. Typical USSBS Nagasaki Damage Analysis Sheet

—4,600 feet from GZ. Group 4. Building 10, looking northwest.

Figure 7. Typical USSBS Nagasaki Postattack Photograph

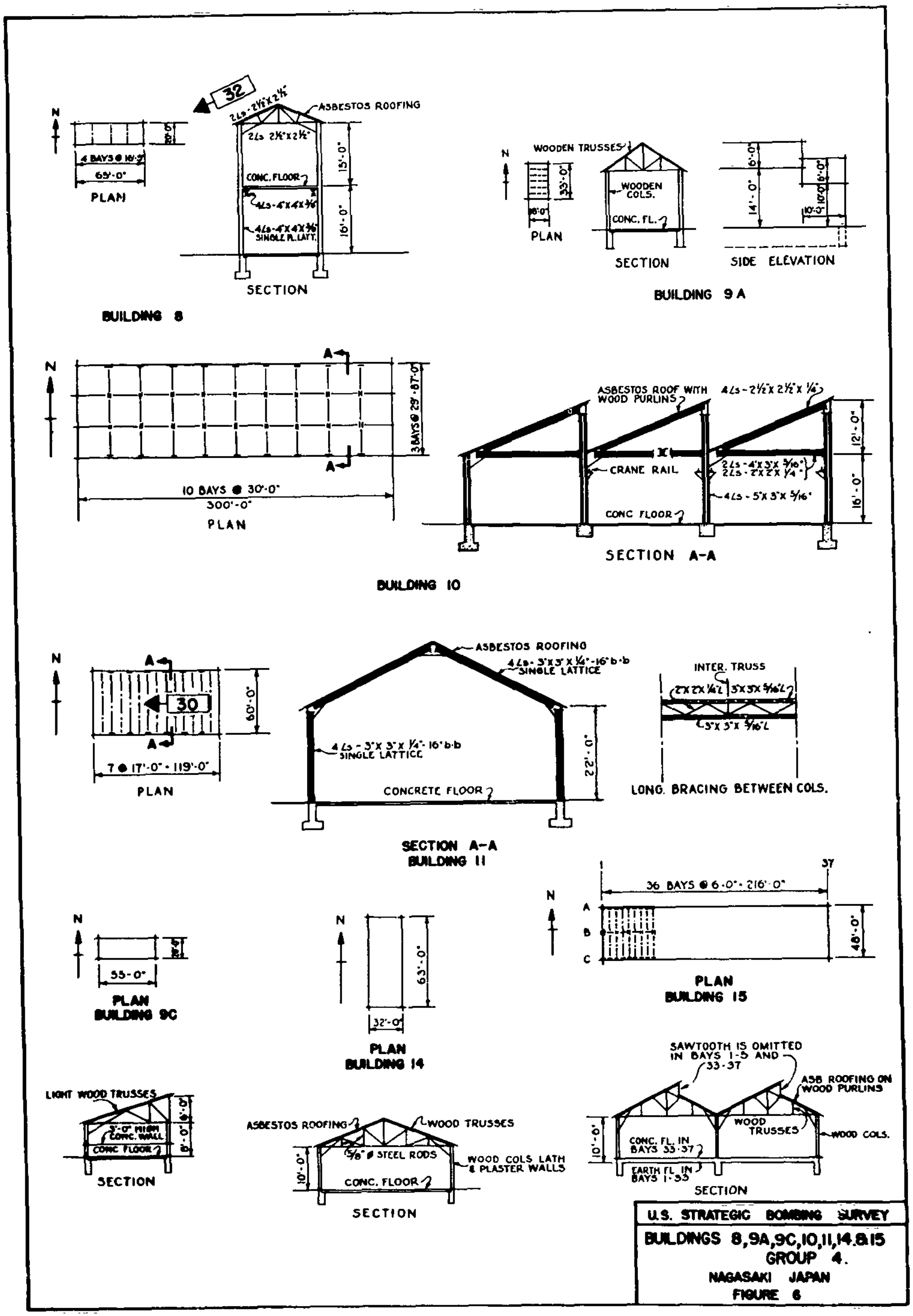


Figure 8. Typical USSBS Nagasaki Building Construction Details

Nagasaki CALCULATIONS Group 4
Building 10

MATERIAL QUANTITIES

a) Roof $\left(\frac{1}{4}/12\right)(92)(300) + \left(\frac{3\times3}{144}\right)(47)(300) = 575 + 881 = 1456$

b) Exterior walls

$(\frac{1}{4}/12)(300+87)(2)(22) + \left(\frac{3\times3}{144}\right)(6)(300+87)(2) = 355 + 290 - \overbrace{\tfrac{1}{3}(355)}^{windows}$

$= 355 + 290 - 118 = 527$

c) Framing - for one bay

$\left(\frac{1.19}{144}\right)(4)(92) + \left(\frac{2.09}{144}\right)(2)(85) + \left(\frac{0.94}{144}\right)(2)(85) + \left(\frac{2.4}{144}\right)(4)(100) = 3.04 + 2.47 + 1.11 + 6.67$

$= 13.29$

~~d) Interior partitions~~

$13.3 \times 11 = 146 + \underbrace{(4)(300)\left(\frac{3.0}{144}\right)}_{crane\ rails} = 146 + 25 = 171$

e) Floors

\- 0 -

a)	1460	cu. ft.
b)	530	"
c)	170	"
d)		"
e)		"
Total	2160	cu. ft.

Total that is combustible = $\frac{880+290}{2160}$ = 54 %

By IITRI method % of total volume contained in building

Not applicable

cu. ft.

DEBRIS QUANTITIES

a) Roof 70% of covering $= (0.7)(575) = 403$

b) Exterior walls

60% of covering $= (0.6)(240) = 144$

c) Framing

0%

d) Interior partitions

0%

e) Floors

0%

a)	400	cu. ft.
b)	140	"
c)		"
d)		"
e)		"
Total	540	cu. ft

Total material that is offsite debris $\frac{540}{2160}$ = 25 %

Total offsite debris that is combustible - ______ = 0 %

REMARKS

Total debris = 100% of roof covering + 100% of wall covering + 20% of frame

$= \frac{575 + 240 + (0.2)(150)}{2160} = \frac{845}{2160} = 39\%$

Figure 9. URS Data Reduction Sheet for Building Described in Figures 6, 7, 8

Weapon Test Information

This information was, in general, the best documented of all, although relatively few residential, commercial, or industrial type buildings were tested. An example of the type of information and its reduction is shown in figures 10, 11, 12, and 13.

In most cases, construction drawings were part of the test report. Most of the test objects were also well instrumented and, in some cases, theoretical analyses of the predicted building behavior and comparison with actual behavior were given. The photography was more than adequate in all cases.

PRELIMINARY ANALYSIS

Limitations in the data determined the methods for predicting debris production that could be developed during this study. Among these data limitations are the following:

1. At Hiroshima, the weapon's height of burst (HOB) was so great that the greatest overpressure experienced (directly below the burst) was only about 25 psi. In addition, a considerable portion of the damaged area was in the regular reflection region, and thus many buildings in the area were subjected to loadings that had large vertical components. (For a lower burst, as at Nagasaki, Mach reflection would start nearer to surface zero, after which the major loading direction would be horizontal.)

2. The Nagasaki data, though more voluminous than that of Hiroshima, was of much more limited use because of lack of information on prestrike building details and because the photography frequently did not permit estimates of off-site debris to be made.

3. Not all classes of structures deemed to be of interest were subjected to a sufficiently wide range of overpressures; certain classes, e.g., structures over seven stories in height, did not exist in either city.

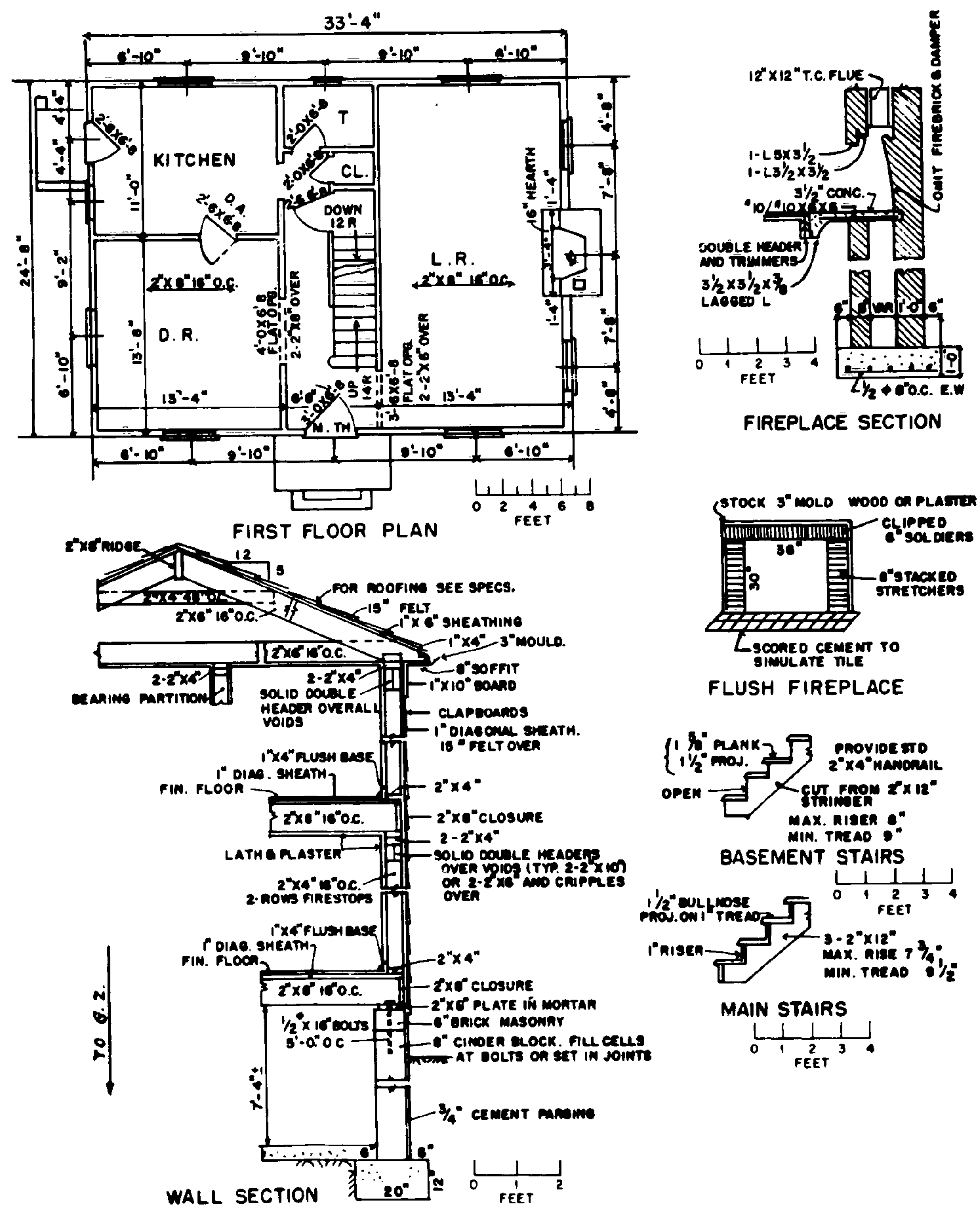
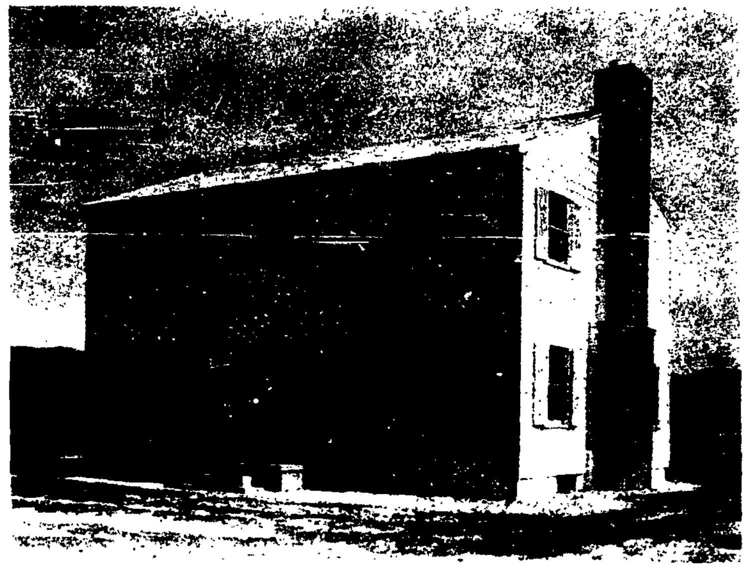


Figure 10. Typical Nevada Test Building Construction Details



House at 3500 ft before the blast.

House at 3500 ft after the blast.

Figure 11. Typical Nevada Test Site Photography for Building Described in Figure 10

—Lower portion of the front section of the roof.

—Upper portion of the front section of the roof.

Figure 12. Typical Nevada Test Site Photography (for Building Described in Figure 10)

Nevada CALCULATIONS

MATERIAL QUANTITIES

a) Roof $(2/12)(33)(28) = 153$

b) Exterior walls $(2/12)(24.6 + 33.3)(2)(17.5) + (2/12)(24.6)(5) - \overbrace{(2/12)(294)}^{\text{windows}}$

$338 + 21 - 49 = 310$

c) Framing Contained in wall, roof, and floor thicknesses

d) Interior partitions

$[(0.208)(8) + 0.11]\,130 = 230$

e) Floors $(2/12)(33)(24)(2) = 264$

a)	150	cu. ft
b)	310	"
c)	0	"
d)	230	"
e)	260	"
Total	950	cu. ft.

Total that is combustible = ______ = 100 %

By IITRI method % of total volume contained in building

Not applicable

cu. ft.

DEBRIS QUANTITIES No debris at 7500' range. At 3500', debris =

a) Roof 100% = 150

b) Exterior walls 40% = $(0.4)(310) = 124$

c) Framing 0%

d) Interior partitions 30% $= (0.3)(230) = 69$

e) Floors 0%

a)	150	cu. ft.
b)	120	"
c)		"
d)	70	"
e)		"
Total	340	cu. ft.

Total material that is offsite debris $\frac{340}{950} = 36$ %

Total offsite debris that is combustible = $\frac{340}{340}$ = 100 %

REMARKS

Formula for volume of partitions is $[(0.208)(\text{height}) + 0.11]$ length

Offsite debris is 36%, total debris is virtually 100%

Figure 13. URS Data Reduction Sheet for Building Described in Figures 10, 11, 12

4. In the weapons tests, not all types of structures were tested. In many instances only portions such as individual panels were tested.

5. Although in many cases the Hiroshima and Nevada Test Site data permitted estimates to be made of the portion of debris that remained on building sites, these estimates were of a much lower order of accuracy than were estimates of the total amount of debris (off-site as well as on-site) produced by the building. Because of this fact, no attempt was made to develop techniques for predicting off-site debris quantities.

For these reasons (and others) the study required, in addition to a thorough analysis of the raw data, a knowledge of construction details and practices, and an understanding of the principles of structural response to dynamic (shock) loads.

Attack (Weapon) Parameters

Of the attack parameters shown in the last chapter to be of importance, it was found that available information would permit debris predictions as a function of overpressure to be made for shock waves in the Mach reflection region (that is, with flow nearly parallel to the ground surface) for weapons of approximately the size of those used on Hiroshima and Nagasaki, i.e., approximately 20 kilotons. (Note that where a precursor does not form, static overpressure can be used to determine dynamic pressure, and peak overpressure together with yield provide a measure of shock wave duration.) There were insufficient test data to allow detailed extrapolation of the kiloton range data directly to larger yield weapons (i.e., with longer duration shock waves); but, as described later, collateral sources permitted estimates to be made for a yield 1000 times greater than 20 kilotons, i.e., 20 megatons.

Thus, in the following, no debris prediction methods are given for structures subjected to shock waves in the regular relfection region, and the effect of increasing positive duration of the incident shock waves is not given in detail.

Target (Building) Parameters

Among the target, i.e., building, parameters discussed in the previous chapter, it was found that the Hiroshima, Nagasaki, and weapon test information could be used to prepare debris prediction curves only for certain classes of structures. There are six of these classes, described in detail in the next chapter:

1. Industrial structures consisting of a light steel framework covered by lightweight wall and roofing materials (termed Steel Frame, Industrial-Light),

2. Industrial structures consisting of a heavy steel framework (used to support a heavy crane) also covered by lightweight wall and roofing materials (termed Steel Frame, Industrial-Heavy),

3. Multistory structures with either steel or reinforced concrete framework constructed to withstand earthquake loads (aseismic design) (termed Steel or Reinforced Concrete Frame, Commercial-Heavy),

4. Multistory structures with either steel or reinforced concrete framework not specifically designed to withstand earthquake loads, covered with relative lightweight, curtain-wall panels (termed Steel or Reinforced Concrete Frame, Commercial-Light),

5. Structures with unreinforced brick or masonry load-bearing walls (termed Brick Load Bearing),

6. Structures with wooden frames and light walls, not designed for industrial use (termed Wood Frame).

Dikewood Corporation[31], which also used Hiroshima and Nagasaki data to devise means for estimating human casualties, arrived at (not too surprisingly) a very similar set of building classes. The categories they adopted, and their abbreviated designations are as follows:

a. Light Steel Frame (LSF) more particularly limited to structures with such frames of two stories or less, <u>and</u> 30 feet or less in height;

b. Heavy Steel Frame (HSF) more particularly limited to structures with such frames of two stories or less, or structures with light steel frames of two stories or less but greater than 30 feet in height;

c. Japanese Reinforced Concrete (JRC) by which is meant structures of aseismic design;

d. American Reinforced Concrete (ARC) by which is meant structures of non-aseismic design with reinforced concrete frames or with steel frames if the building contains more than two stories;

e. Brick (BR) i.e., structures with brick walls;

f. Wood Frame (WF).

The categories are completely compatible, though for purposes of clarity, in this report neither the Dikewood designation nor abbreviations were used.

For convenience, in table 1 a correlation is established between Physical Vulnerability building descriptions and numerical designations of the National Fallout Shelter Survey[31], and the building categories used in this report.

Table 1

COMPARISON OF PHYSICAL VULNERABILITY CODES WITH URS DESIGNATIONS

Type of Facility	PV Codes	URS Designations
Wood-framed buildings		
Single-story or multistory dwelling	21	Wood Frame
Single-story or multistory commercial or industrial building	22	
Wall-bearing buildings		
Single-story dwelling	31	
Single-story commercial or industrial	32	
Two-story dwelling	34	Brick Load Bearing
Two-story commercial or industrial	35	
Three- to five-story buildings	36	
Steel-framed buildings		
Single-story very light steel frame, industrial or commercial	41	Steel Frame, Industrial Light
Single-story light steel frame, no cranes or cranes of less than 10 tons, industrial	42	
Multistory, conventional design, commercial	43	Multistory, Steel or Reinforced Concrete Frame, Light
Multistory, light industrial	44	
Single-story, industrial with:		
10-25 ton cranes	45	Steel Frame, Industrial, Heavy
30-50 ton cranes	46	
60-100 ton cranes	47	
Over 100 ton cranes	48	
Steel-frame multistory, earthquake resistant	49	Multistory, Steel or Reinforced Concrete Frame, Heavy
Reinforced concrete frame buildings		
Multistory, conventional commercial	57	Multistory, Steel or Reinforced Concrete Frame, Light
Multistory, industrial	58	
Multistory, earthquake resistant	59	Multistory, Steel or Reinforced Concrete Frame, Heavy
Multistory, windowless blast-resistant design	91	

Chapter 3

RESULTS

From the data discussed in the previous chapter, graphs were prepared relating total debris production* (in terms of percentages of the total material contained in a building) to peak incident overpressure for 20-kiloton and 20-megaton weapons. Individual graphs are presented for each of the six building categories, and the information is summarized on two combination graphs for each of the weapon yields, on each of which debris production curves for all building categories are plotted. Details of the analyses leading to the graphs are discussed in the following paragraphs.

STEEL FRAME, INDUSTRIAL BUILDINGS (LIGHT AND HEAVY)

Buildings in this category are typical of buildings in industrial areas, consisting of a steel framework generally covered with either corrugated steel, corrugated asbestos, or flat sheet metal panels. This type is sometimes produced as a prefabricated modular unit, that is, a basic unit that can be repeated to increase the size of a building. Also, in this same category, can be included buildings that are self-framing, that is, in which the wall panels provide all the necessary support for the roof.

From the available data, only two classes were distinguishable, light steel and heavy steel frames. All buildings without cranes or with cranes of 10-ton capacity or under are considered light; all those with cranes of greater than 10-ton capacity are considered heavy. The columns of the latter class of buildings are designed to withstand large crane loads; they are stronger and more massive than those of the former class and are, therefore, better able to withstand blast loads.

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*Note: total debris comprises both on-site and off-site debris.

Industrial buildings surveyed in Hiroshima and the few industrial type buildings of the weapons tests were all of the light-steel frame type. On the other hand, Nagasaki had mostly heavy-steel frame buildings.

Buildings having steel frames and frangible, or relatively low-strength, walls and roofs are largely drag sensitive, that is, the walls and roof, which comprise a relatively small portion of the total material in the building, will, because of their low ductility, or the weakness of their connection to the frame, be stripped away from the frame early in the diffraction phase and at low overpressure levels. This covering failure occurs quickly and there is a rapid equalization of pressure around the frame members. Consequently the frame receives a relatively short diffraction phase loading, but a much longer drag phase loading. At what overpressure the frame will fail is determined largely by the duration of loading relative to the natural period of vibration of the frame; in general, the longer the loading time, the lower the overpressure needed to make the frame fail.

As the data pertaining to these types of buildings were studied, a typical failure pattern became apparent. At a low overpressure, all of the siding and roofing failed and left only the frame standing. The frame, although possibly distorted, could remain standing unless the dynamic overpressure was large enough to cause frame collapse due to drag. Thus, as an example, if the overpressure necessary to make the covering of a structure fail was 2 psi, and that required to collapse the frame was 13 psi, for any overpressure between 2 and 13 psi the amount of debris produced by the structure would remain constant at that quantity contained in the covering (even though frame distortion could occur). When subjected to an overpressure of 13 psi or greater, the frame would collapse, at which point the quantity of debris produced would rise to a maximum, that is, 100 percent of the original building.

The generic shape of a curve of debris production (as measured by the ratio of actual debris to total possible debris in percent) versus overpressure would be a straight line at a distance from the origin representing the percent of the total material volume contained in the walls and the roof covering. This line would extend over a large range of overpressure. At its lower overpressure end, it would break sharply downward to the zero debris level around the critical overpressure for covering failure, and at its high overpressure end it would break sharply upward to the 100-percent debris level around the critical overpressure for frame collapse.

The curves of debris production (as a percent of total building material volume) are shown in figures 14 and 15 as a function of incident overpressure for light and heavy steel frame industrial buildings. The details of the development of these curves are discussed below.

The Hiroshima, Nagasaki, and weapon test data indicated that failure of walls and roof would begin at approximately 1.5 psi. The weapon test data also indicated that such failure would occur at approximately the same overpressure for both corrugated steel and asbestos siding and, therefore, no distinction is made between overpressures necessary to make different types of covering materials fail. Since the same covering materials are used for both light and heavy steel frame buildings, both curves start at the 1.5-psi level.

The horizontal line on both figures 14 and 15 is the percent of total building materials represented by frangible coverings. While analyzing the Hiroshima and Nagasaki data to determine this percentage, it became apparent that there are differences between Japanese and American practices in the construction of steel frame buildings. The Japanese use a great deal of wood, both as purlins for the roof covering and as girts to hold the siding in place, and also for roof sheathing. This practice does not affect the strength of a building. However, the presence of the wood causes estimates of debris to differ for Japanese and American buildings, since it changes the volumes of the component parts and, hence, their relationship to the total volume. In order to use Hiroshima and Nagasaki information for predicting debris for American buildings, material quantities were recalculated, with steel replacing wood.

Then, the total volume of material contained in the light steel frame (Hiroshima) buildings and the heavy steel frame (Nagasaki) buildings, and the portions of these totals contained in the coverings and frames of the buildings were computed.

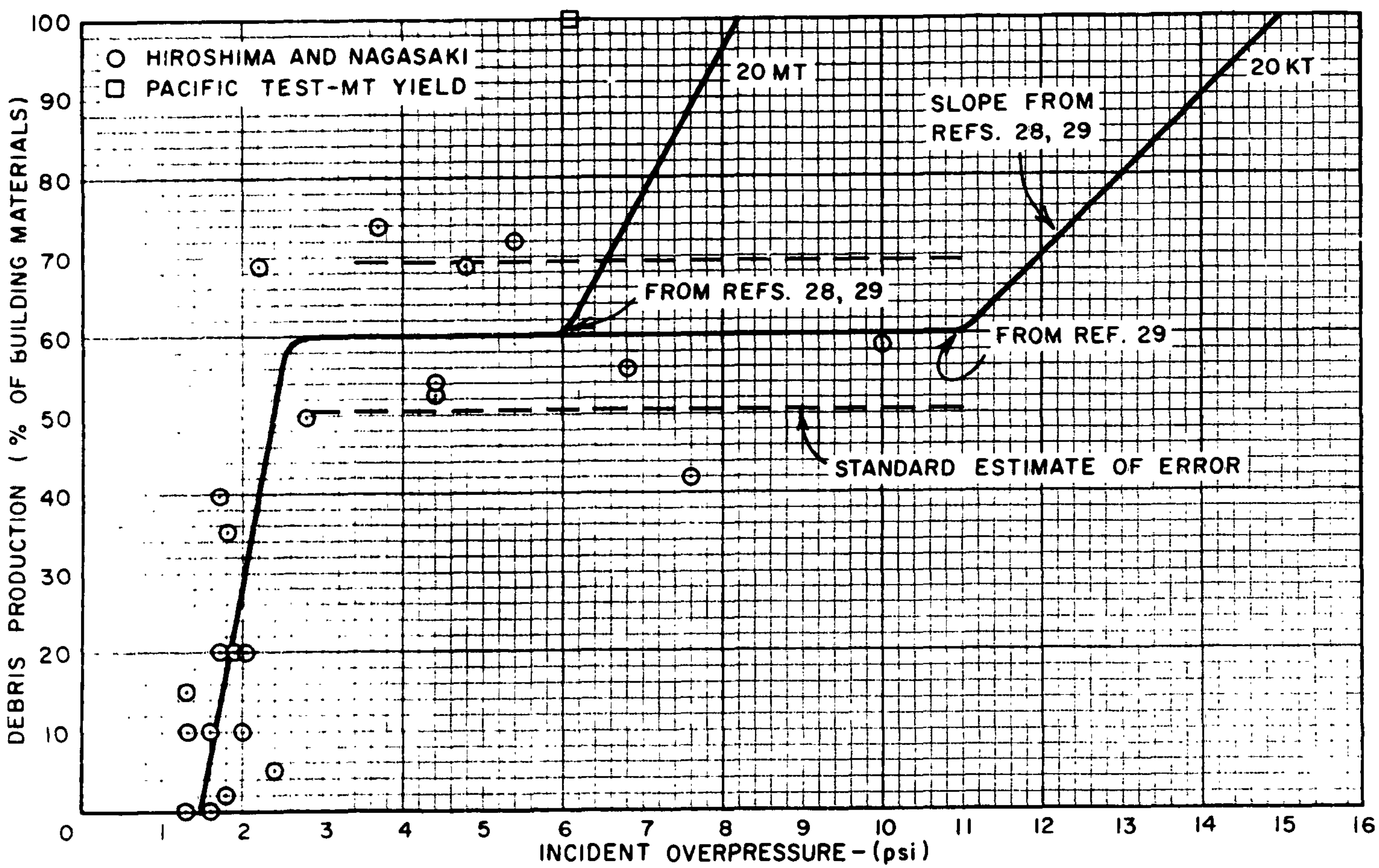

Figure 14. Debris Production vs. Overpressure; Steel Frame, Industrial, Light Structures

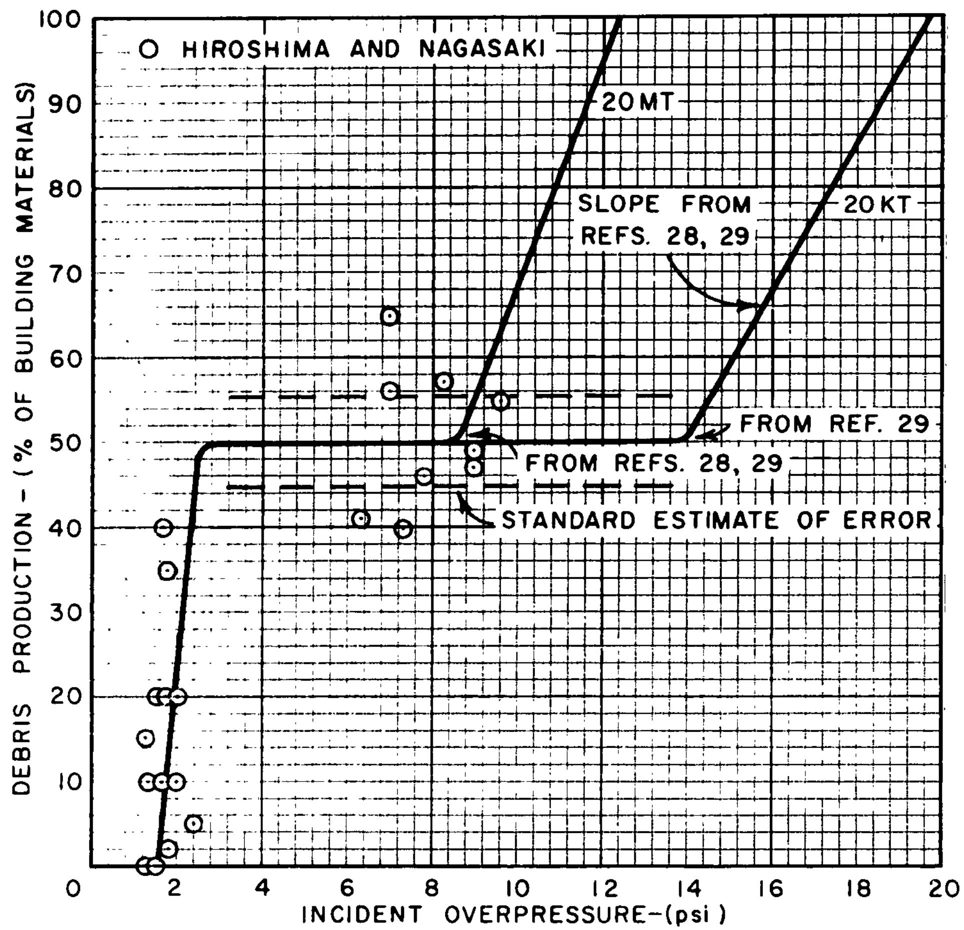

Figure 15. Debris Production vs. Overpressure; Steel Frame, Industrial, Heavy Structures

As shown on figures 14 and 15, these computations indicated that for the light steel frame buildings, 60 percent of the total building volumes and, for the heavy steel frame buildings, 50 percent of the total building volumes were contained in the coverings.

The figure for light steel frame buildings was checked by comparing it with one from an actual American steel frame building. Drawings were obtained from the Soule Steel Company for one of their standard light frame buildings,and it was found that the frame of the American building contained 40 percent of the total material volume, which checked exactly with Hiroshima experience.

The overpressures at which total frame collapse would take place were difficult to predict since actual instances of total collapse were rare. Approximate values were taken from the criteria given in reference 28 for severe damage to such structures. Since this implies imminent collapse of the frame, the overpressure levels (for kiloton and megaton weapons) at which reference 28 suggests that severe damage occurs, were taken as the points at which frame collapse begins. To obtain some measure of the overpressure at which collapse is complete, the ductility of the frame members was assumed to double, and the curves of reference 27 (which enable estimates to be made of the overpressure required to overcome building resistance) were applied. The curves of reference 27 were also used to check the point at which failure is assumed to begin for megaton range weapons. This was done by assuming an increase in loading duration by a factor of approximately 10.

In addition to the basic curves, figures 14 and 15 also present the standard error of estimate of the data points about the horizontal portion of the lines. The standard error bands show the range of debris (as measured by the percent of total material volume) that would be produced by approximately two-thirds of buildings of these types when subjected to the indicated overpressures (assuming, of course, that the data points are distributed normally about the horizontal lines).

Because of paucity of information, figures 14 and 15 are not adequate to show any effects of orientation of the building with respect to the direction of travel of the blast front or of one structure shielding another. However, it might be noted that, in Nagasaki a steel frame structure oriented with its long axis normal to the direction of travel was partially collapsed, while an adjacent similar building, oriented with its long axis parallel to the direction of travel, was still standing.

MULTISTORY STRUCTURES WITH CONCRETE OR STEEL FRAME (HEAVY AND LIGHT)

General

Two problems were of primary concern in the analysis of the available data for multistory reinforced-concrete and steel frame structures. First, it was necessary to determine which structures at Hiroshima and Nagasaki were examples of their class, but without some unusual feature that would grossly affect structural behavior or debris production. Second, for the data to be usable, it was necessary to determine the difference between typical Japanese and U.S. structures to modify the data for application to typical U.S. cities. The problem was complicated by the fact that no structures in this class were destroyed during the atomic bomb attacks on Japan and that data from nuclear weapon field tests on these classes of structures were found to be extremely limited.

Since the graphs presented later in this section are based primarily on the data obtained from the atomic bomb attacks on Japan, a brief discussion of Japanese construction practices for multistory buildings is pertinent. The 1923 earthquake in Japan caused such severe damage to structures that an earthquake code was adopted in 1924[4-9]. Some of the more important provisions as far as multistory reinforced concrete or steel structures were concerned are as follows: Structures were designed to resist a lateral load equal to one-tenth of the weight of the building. Steel and reinforced-concrete frame structures were limited to 100 feet in height, and continuity of construction was required. Because of these and other requirements, the structures were, in the judgment of the USSBS survey teams, "about 50—70 percent stronger" and heavier than U.S. structures (except along the West Coast, where earthquake-resistant design is required for many structures).

These Japanese earthquake code requirements are very important from the standpoint of the postattack data obtained from Hiroshima and Nagasaki and their application to debris production in typical U.S. cities. In general, the code resulted in structures that were as monolithic as possible through the use of heavier members, rigid connections, and continuous reinforcement. Diagonal bracing and reinforced-concrete shear walls made most of the major structures ideally suited to resist large blast forces without undue loss of structural integrity between the frame, walls, and floors. In fact, there were no structures in this class that suffered collapse during the atomic attacks. In reference 5 it is stated, "Thus, the heavy, strong multistory steel-or concrete-frame structures were damaged only in an area relatively near the point of detonation, and their burned-out but otherwise undamaged structural frames rose impressively from the ashes of the burned-over section where occasional piles of rubble or twisted-steel skeletons marked the location of brick or steel-frame structures."

Of the literally hundreds of structures surveyed by USSBS 4-9/ at Hiroshima and Nagasaki, it was found that only about 60 could be classified as multistory, reinforced concrete and steel frame buildings. Of these, 45 were of earthquake-resistant design and 15 were not. Although the earthquake-resistant structures ranged from 2 to 7 stories, the large majority had only 2 or 3 stories. The floor area of the individual buildings varied from 4,300 to 93,400 square feet, and they were subjected to overpressures ranging from 8.9 to 36 psi. The non-earthquake-resistant structures were 2 and 3 stories in height, with a total floor area of from 1,200 to 80,100 square feet, but most were small, compact, 2-story structures, hardly typical of the large multistory frame structures found so frequently in U.S. cities.

The number of structures from which information on debris production could be derived was decreased further by what might be termed atypical conditions. Thus, the heights of burst used in Japan were great enough that regular reflection occurred at relatively low overpressure levels. It is estimated, for example, that at Nagasaki, the regular reflection region extended to the 37-psi overpressure level, while at Hiroshima, regular reflection occurred down to the 10-psi level. Current attack doctrine, which emphasizes lower relative burst heights, especially for megaton-range weapons, implies that regular reflection, if it occurs at all, would only exist at very high overpressures. This tacitly assumes that structures in the regular reflection region would be completely demolished or, conversely, that structures with less than complete destruction would all be subjected to shock wave flows that are nearly parallel to the ground surface. Many of the Japanese structures, because they were located in the regular reflection region, were subjected to loadings with a much higher vertical component than they would have experienced were they in the Mach reflection region. These high vertical loads, at a much lower overpressure at Hiroshima than at Nagasaki, caused damage to some roof and floor systems and the generation of debris from these members. This fact had to be considered when comparisons were made of the debris produced in the two cities.

When these, and other data anomalies that could be related to special characteristics of individual structures were taken into account, it was found that the primary value of the Hiroshima and Nagasaki atomic bomb attack data lay in the insight gained into the behavior of well-designed multistory buildings subjected to large blast forces. Because damage to the main structural components varied from zero at the lower overpressures to incipient major structural failure at the highest overpressures experienced, the data were also useful in determining the threshold of major structural damage.

In this process, drawings and photographs were studied in great detail to determine, in respect to known weapon parameters, the exact postattack condition of a particular structural system. For instance, in many cases it was possible to ascertain whether the failure of a beam or column was due to some unusual feature of design, or whether it was indicative of incipient failure of the main structural framing.

This detailed study of individual structures yielded quantitative information on the progressive nature of structural distress with increasing air blast overpressure up to the point of major structural distortions.

During this study, attempts were made to relate the structural damage reported by the USSBS survey teams to debris as defined in this report. (It will be recalled that both structural and superficial damage was reported by these teams.) This was deemed a worthwhile effort since, if successful, the large body of information available for structural damage predictions would be available for debris predictions[28,29]. Although the generic slopes of the curves obtained from the USSBS structural damage information were used to assist in extrapolation of data for this study, no relationship could be derived between the structural damage information and debris production. There were two primary reasons for this: first, the structural damage percentages reported by the USSBS teams were based on floor damage, which is, of course, a direct indication of the postattack "usability" of the building but not necessarily a good indicator of the debris produced; second, because of the relatively low overpressure experienced near ground zero in the Japanese cities, most of the damaged structures in this class were located in the regular reflection region. The consequent high vertical loads produced relatively excessive damage to roof and floor slabs and resulted in accentuated percentages of structural damage.

For the purposes of this report only two rather general categories of multistory reinforced-concrete and steel frame structures are considered, viz., earthquake resistant, and non-load bearing panel wall construction. The lack of adequate information, as discussed previously, required a certain amount of rationalization before the curves presented in this section could be constructed. The selection of the two categories was essentially dictated by the nature of the available data, which for multistory buildings are primarily restricted to aseismic structures from Hiroshima and Nagasaki. Only a very few examples of non-aseismic panel wall construction were found at Hiroshima and Nagasaki, and there was no modern multistory thin curtain wall construction typical of U.S. cities. However, since information is available from nuclear field tests as well as Japan for brick and concrete block panel walls, the curves were constructed for multistory frame buildings with these types of panels. A short discussion of the development of the curves for the two categories of multistory structures follows.

Earthquake Resistant Design

Debris production for this class of structure starts with the failure of the interior, non-structural partition walls (neglecting, of course, such items as glass and light window framing). Although the actual process of ejection of interior partitions as debris from a building is rather speculative, the failure of partitions under actual air blast loading is fairly well documented. Non-load bearing partitions begin to fail at relatively low overpressure (in relation to strength of the structure) and have collapsed completely prior to major structural distress for earthquake-resistant structures. Both nuclear weapons tests and Japanese experience have shown that typical lath and plaster partitions begin to show distress at 2 to 3 psi. The general nature of the blast wave entering, diffracting, and reflecting within the building--as well as such factors as the percent of window and door openings and the partition orientation--are variable parameters and their individual effects are not determinable from the available data.

The initial failure of a portion of the interior partition walls does not create a debris problem in the same manner as failure of other portions of a structure, and is therefore treated differently in this section. By the very nature of the problem, there is actually no debris outside the building until a large portion of the partition walls have failed, permitting the debris to be ejected out the windows. Although the data on blast effects at Hiroshima and Nagasaki were frequently obscured by the effects of fire in the interior of many reinforced-concrete structures, the useful data indicated that a large percentage (approximately 80 to 90 percent) of the interior lath and plaster walls were reduced to debris at about 10 psi. It was impossible to determine the actual quantity of debris ejected from individual buildings at this overpressure, but where fire did not occur, a considerable portion of rubble remained in the buildings.

At about 25 psi, it was apparent from the data that all partition walls had failed and, in many cases, the debris entirely ejected from the building. (It should be mentioned, however, that in some surveyed buildings only an insignificant portion of the partitions failed at the 25 psi level. The reasons for this are unknown, but it was usually observed in the smaller well-built buildings with minimum window openings.) In any event, for this investigation, the above overpressure limits were used to establish the initial portion of the graph shown in figure 16 for kiloton-yield weapons. It was assumed that, for overpressures less than 10 psi (with kiloton-yield weapons), no partition debris would be ejected from the building, and at 25 psi, 100 percent of partition debris would be ejected from the building. For the structures reviewed, the interior partition walls were found to comprise approximately 15 percent of the total material quantities, which accounts for the 15-percent plateau shown in figure 16.

As has been pointed out, in the Japanese cities there were very few multistory structures of this class in the Mach reflection region subjected to overpressures high enough to cause major damage to the structural elements and, in fact, none of the aseismic-designed structures failed. Furthermore, a review of nuclear weapon field tests revealed no direct information on multistory reinforced-concrete structures applicable to this study. Because of the lack of "experimental" information, it was necessary to construct the portion of the curve above the 15-percent debris level from other considerations.

The threshold overpressure at which major structural damage begins to produce large quantities of debris was established primarily by a study of the behavior of three large multistory structures at Nagasaki, all located in the Mach reflection region and all subjected to an overpressure of approximately 35 psi. Gross distortions of the structural frame in all of the buildings as a result of the large lateral forces were apparent. It is known that well-designed reinforced-concrete members can undergo relatively large plastic deformations, resulting in elongation of the reinforcing steel and spalling of the concrete, and yet will support considerable load. It is also obvious that very little debris will be produced even though collapse is imminent. Examination of the photographs of the three Nagasaki structures indicated that they were on the "threshold" of structural damage which would probably have produced considerable debris. This conclusion essentially established the upper limit of 15-percent debris line (i.e., 0 percent structural debris, 100 percent interior partition debris) on the graph at 35 psi.

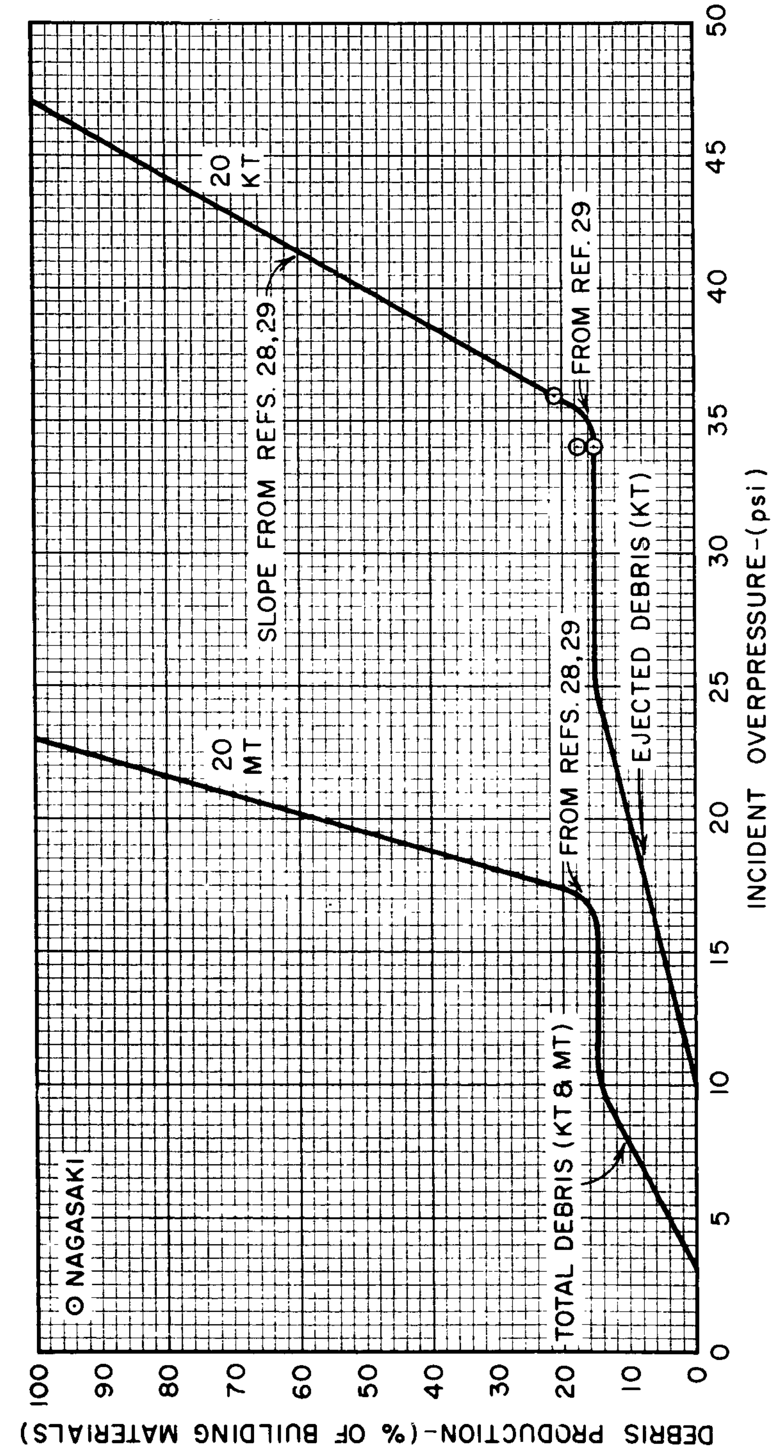

Figure 16. Debris Production vs. Overpressure; Multistory Steel or Reinforced Concrete Frame, Heavy Structures

It should be noted that, although only the three structures mentioned were close to or slightly above the threshold pressure, other structures subjected to lower overpressures indicated progressively increasing structural damage as higher overpressures were approached. This information increased the confidence in the threshold pressure level finally selected.

As mentioned previously, during the original USSBS surveys of the Japanese cities, data were gathered on structural damage for individual structures, which the USSBS teams defined as, "Damage to principal load-carrying members (trusses, beams, columns, load-bearing walls, floor slabs in multistory buildings), requiring replacement or external support during repairs. Light members such as purlins and rafters are not included." This was recorded by the survey teams as a percent of building damage based on total floor area. Using these percentages, Bowman[32/], developed curves for percent of structural damage as a function of range for various classes of structures subjected to shock wave from a "nominal atomic bomb" (ref. 29, 20 kilotons, 1850-foot HOB). Although no direct correlation between damage percentages given by the USSBS teams and debris percentages calculated by URS were obtained during this investigation, it was assumed that Bowman's analysis of the damage data showed the rate of increase of overpressure required to cause total structural collapse, i.e., 100 percent debris. Therefore, the curve in figure 16 was extended linearly from the 15-percent debris level at 35 psi to the 100-percent level at 47 psi for kiloton-yield weapons using the slope from Bowman.

The point on the curve of figure 16 at which failure of the structural frame would begin to produce significant debris was determined from reference 28 which indicated that a shock wave from a megaton-range weapon with a peak overpressure of only one-half that of a shock wave from a kiloton-range weapon would cause the same degree of structural damage. (It will be recalled that building frames are drag-sensitive targets. This implies that long-duration shock waves will be more effective than those of short duration.) This conclusion was strengthened by calculations of peak loading pressures required to overcome structural resistance, following reference 27, in which loading durations were assumed to increase by a factor of approximately 10. These also indicated that the long-duration shock waves required only approximately one-half the peak loading pressure as did one of short duration to cause the same degree of damage. Accordingly, the point at which frame collapse began for a 20-megaton weapon was set at 17 psi. It was further assumed that the larger weapon would require the same relative overpressure increase to produce total frame collapse as did the smaller weapon, which established the "22 psi, 100% debris" point on the megaton curve.

The ejection of interior partition debris from a building is quite sensitive to the positive phase duration of the blast wave, that is, the rubble created by the diffraction and reflection of the blast wave within the structure is primarily drag-sensitive. At 10 psi overpressure (0 percent ejected debris for kiloton-yield weapons), the peak wind velocity is approximately 290 mph and the total wind duration is about 7 seconds for a 20-megaton yield weapon and 0.7 seconds for a 20-kiloton yield weapon. The quantitative effect of this increased duration is not known but, qualitatively, it would appear that partitions would be ejected from the building upon failure. This assumption is reflected in the position of the lower portion of the 20-megaton curve.

Non-earthquake-Resistant Design

As discussed in the previous section, there were insufficient data for the multistory class of structures from the Hiroshima and Nagasaki atomic bomb attacks to establish reliable debris curves. However, curves could be derived for the composite elements of the structure, such as brick panel walls, for which considerable nuclear field test data exists.

The production of debris from multistory panel wall structures would be initiated by failure of the exterior panel walls during diffraction of the blast wave around the structure. Since this failure would expose the weaker interior partition walls, most probably they would fail simultaneously with the exterior walls. (It is conceivable that an overpressure exists, for a short duration blast wave, that would just cause the exterior panel walls to fail, but not the interior partitions, but such a refinement is considered unjustified.)

As the blast wave engulfs the structure, the walls fail relatively early in the loading phase (assuming the overpressure is high enough to cause failure), prior to their transferring sufficient load to the frame to cause frame failure. This is because the impulse is a function of both overpressure and duration of the blast wave and, although the instantaneous reflected overpressure can be quite high (more than twice the side-on overpressure), the time to failure is very short. Also, panel or curtain walls are generally of insufficient structural strength to transfer through their connections, even under static conditions, the magnitude of load necessary to cause frame failure.

Although damage to the composite structure is dependent on the overpressure, the structure remaining after failure of the walls is primarily drag- or dynamic-pressure-sensitive. Experimental data from Hiroshima, Nagasaki, and nuclear field tests show that the magnitude of dynamic pressure at the overpressure level required to make conventional panel walls fail, is insufficient to cause frame failure. This, of course, suggests that debris production for this class of structures will be in two distinct phases. That is, the exterior walls and non-structural interior partitions will initiate debris production by failing at a relatively low overpressure level, and only a small increase in overpressure will be required to produce 100 percent debris for these components. A considerably higher overpressure with accompanying higher drag loading will be required to initiate debris production from the structural framing and floor system.

For this investigation, the initial portion of the debris curve shown in figure 17 was developed primarily from the experimental data. As indicated, debris production is initiated at about 6 psi overpressure, where the panel walls begin to fail. At about 13 psi overpressure, the exterior panel walls and interior partition walls are 100 percent debris. This establishes the minimum overpressure for the plateau in the curve. The 65-percent debris level is a function solely of building material quantities and was determined for this graph from calculations for several representative buildings at Hiroshima and Nagasaki. Although the data available were almost entirely for kiloton yields, the initial portion of the curve is identical for both kiloton and megaton yields since the walls are primarily diffraction-sensitive. Because of the almost complete lack of experimental information on the ultimate failure of multistory panel wall buildings, the same procedure used to establish the upper portions of the curves for a multistory aseismic design structure was used to develop the upper portion of the curves shown in figure 17.

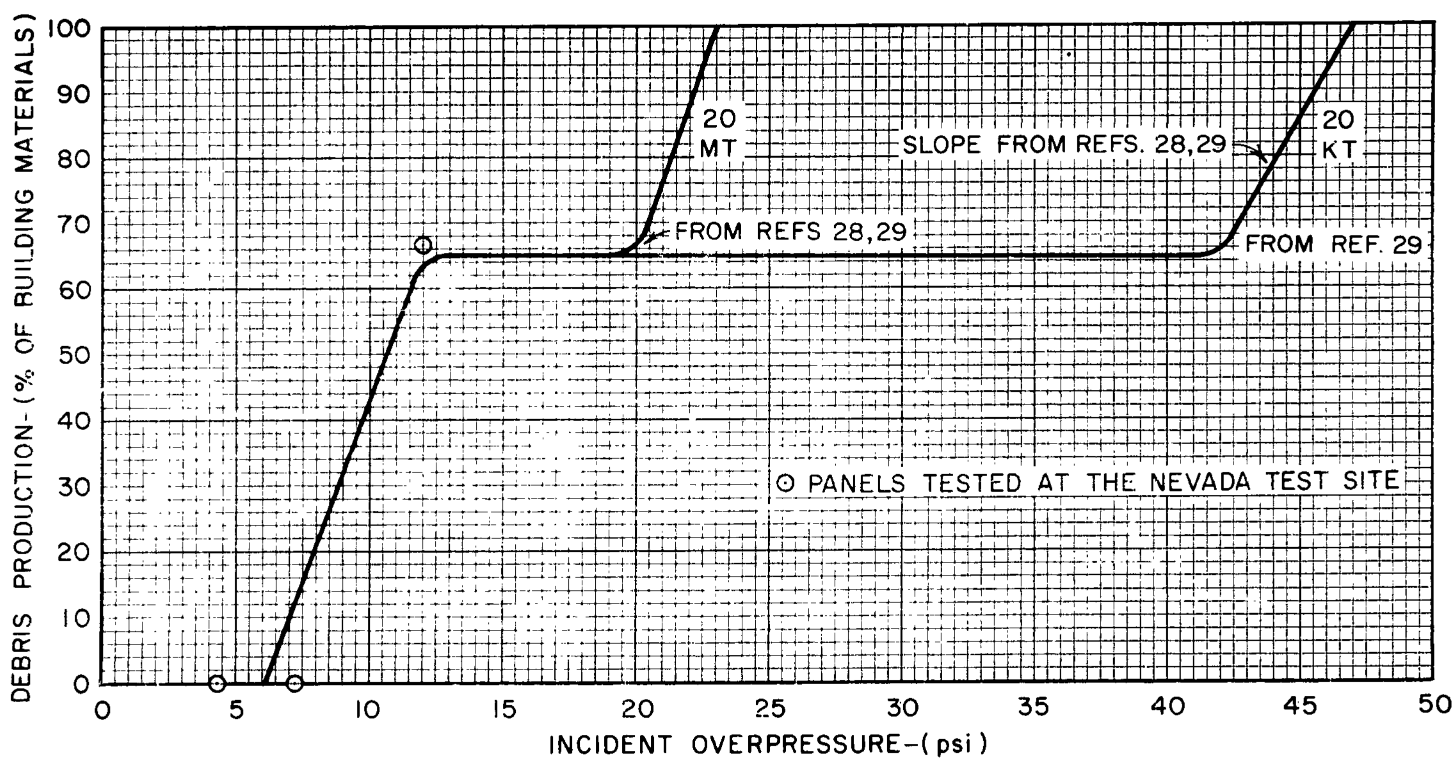

Figure 17. Debris Production vs. Overpressure; Multistory Steel or Reinforced Concrete Frame, Light Structures

BRICK LOAD-BEARING-WALL BUILDINGS

This category includes all of those buildings that have either unreinforced brick or masonry walls with no frame. The weight of the roof and the floors resting on the walls helps strengthen them. This type of building is very common for one- and two-story residences and row apartment buildings. Also, many small industrial shops are constructed with block or brick walls, no frame, and a truss roof, thereby placing them in this category.

Most of the data on such structures for this study came from Hiroshima, where brick load-bearing wall buildings suffered damage ranging from complete destruction to very minor roof disturbance. There were fewer examples of this type in Nagasaki but, again, there was a broad range of damage.

The weapons tests confirmed what was determined from the Japanese surveys. There was an example of a two-story row apartment house in one of the shots of Operation Greenhouse, and there were some two-story brick residences in Nevada. There were also tests on brick panel walls, but such panels should not be expected to behave as would panels of the same materials in normal structural walls. Some tested panels had no windows and no weight bearing on them other than their own, which would tend to make them more vulnerable to blast, since pressure could not be equalized on both sides of the panels until they collapsed.

There was also some discrepancy between the behavior of panels with windows in the weapon tests, and walls of similar materials in actual buildings at Hiroshima and Nagasaki. It might be expected that both would fail at approximately the same overpressure, but the panels always withstood overpressures that caused partial building failure. Two reasons can be given for this. First, because of the truss-type roof construction prevalent in the Japanese buildings, the roof fails at a fairly low overpressure, thus decreasing the structural unity of the building. Without the weight and stiffening effect given by the roof, the walls are weakened. Early failure of the roof would not be peculiar to Japanese buildings. Most American brick residences have wood-truss roofs, and any roof system other than reinforced concrete would not offer significant resistance to blast.

Second, the horizontal component of blast force causes deflection and movement of the entire building, and this movement strains and weakens the mortar bond between bricks. Movement would not be as great in a test panel framed by massive reinforced concrete members designed not to fail or so affect the response of the panel under observation.

There were not enough data to make a distinction between one-story and multistory buildings. However, up to a point, multistory buildings can be considered as stacked one-story buildings, so the difference, if any, should not be great. The study includes information on buildings as high as three stories. Above this height, there is a possibility that failure will be progressive, that is, collapse of the roof and upper walls can cause collapse of all the floors. This, in turn, will weaken the remaining walls, which are more likely to collapse in a tall building, where their height makes them inherently less stable (with the lateral support of the floor removed) than in buildings of only two or three stories. Figure 18 shows the debris production curve for brick, load-bearing wall buildings. The curve was drawn from both Japanese data and data from the weapons tests. Also plotted in figure 18 is the standard error in estimating overpressure from percent debris, a measure of the spread of the data about the basic line*.

This category of buildings is essentially diffraction-sensitive, which means that the majority of damage occurs within a short time after shock wave arrival. As a consequence, the overpressure necessary to cause a given amount of debris should not increase with shock wave duration or weapon yield. Thus, the same curve is to be used for both 20-kiloton and 20-megaton weapons. The reader is reminded, however, that the magnitude and duration of drag phase loading has a critical effect on debris distribution.

These buildings, producing more debris per contained building volume than any other type because of the mass of material in the walls and the lower overpressures at which they fail, are also more common than any other type of building, at least in the eastern part of the United States.

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* If errors are normally distributed about the line, approximately two-thirds of them will fall within the band shown.

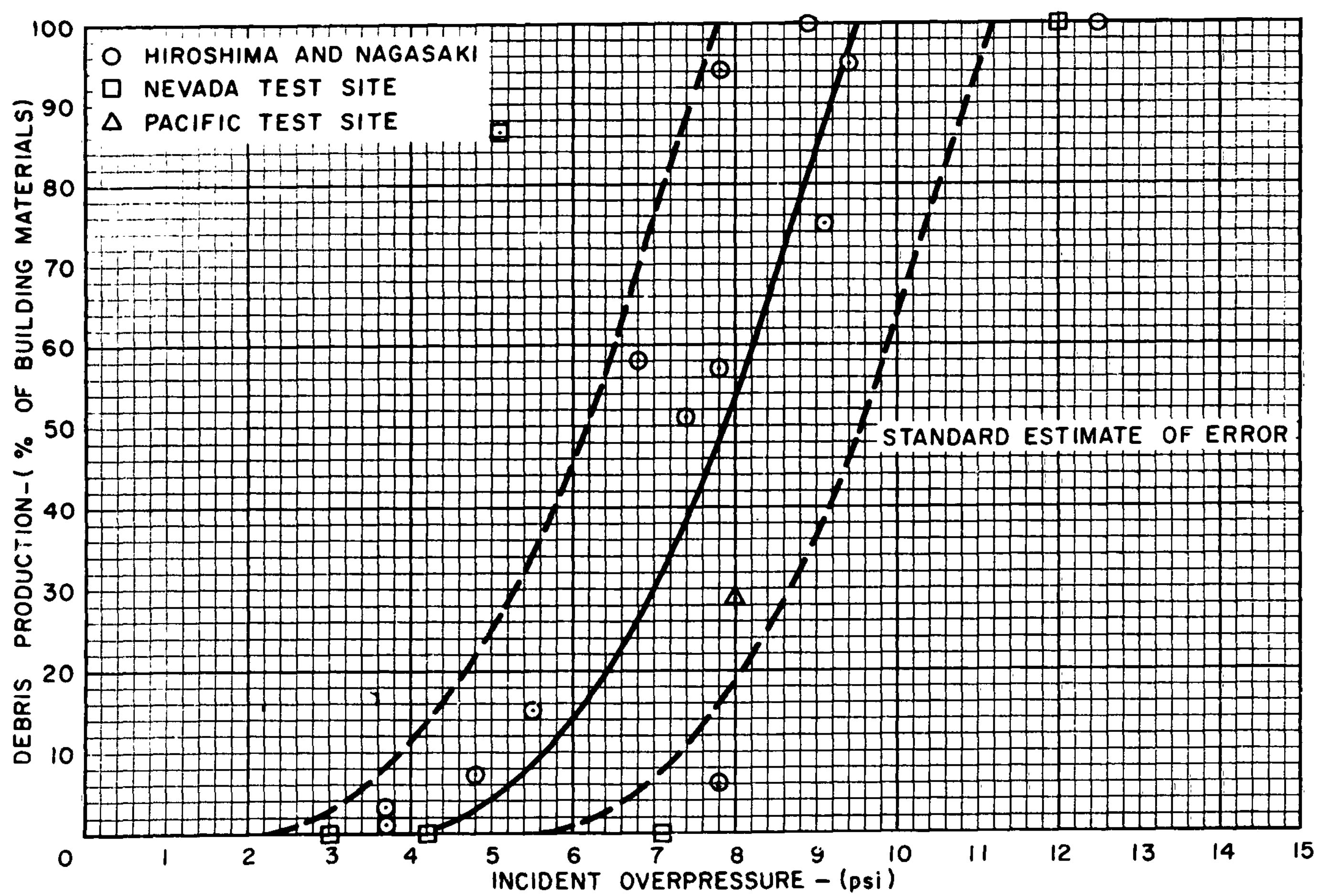

Figure 18. Debris Production vs. Overpressure; Brick, Load Bearing Wall Structures

The resistance of load-bearing brick wall buildings to blast loading can be increased slightly by changing their construction, e.g., a roof of reinforced concrete would be stronger than a wood-truss one, and load-bearing partitions would also add strength.

The Japanese brick load-bearing wall construction was, in general, comparable and, in some cases, stronger than United States construction of the same type. It is felt, however, that the graph is applicable to United States brick load-bearing wall structures.

WOOD FRAME BUILDINGS

This category includes buildings common to all portions of the world. There were many wood frame homes in Japan, and, although there was a considerable amount of fire, very useful data for debris prediction were obtained. Certain weapons tests in Nevada supplemented the findings in Japan.

In the opinion of the Hiroshima survey team, Japanese wood frame construction was weaker than U.S. wood frame construction. However, it is felt that the resistance to blast of American residences in general would not be markedly different from that of the houses in Hiroshima and Nagasaki.

The debris curve (fig. 19) for this category was established from Japanese data and from weapons tests at the Nevada Test site. There was a great amount of scatter in the Japanese data, e.g., at an overpressure of 5 psi. Buildings could be found that had completely collapsed, whereas others were still standing. (The buildings still standing were in a very highly built-up area, and it is conceivable that the incident overpressure would have been higher had the buildings been standing alone. In Nevada a typical wood frame two-story residence was placed far from any other structure. At an overpressure of 1.7 psi, no debris resulted, and at 5 psi, the house was destroyed, leading to the conclusion in the test report that a conventional wood-frame house would be destroyed at 5 psi.

A standard error band about the basic curve is also shown in figure 19 although the data are really too few to afford this band much authority.

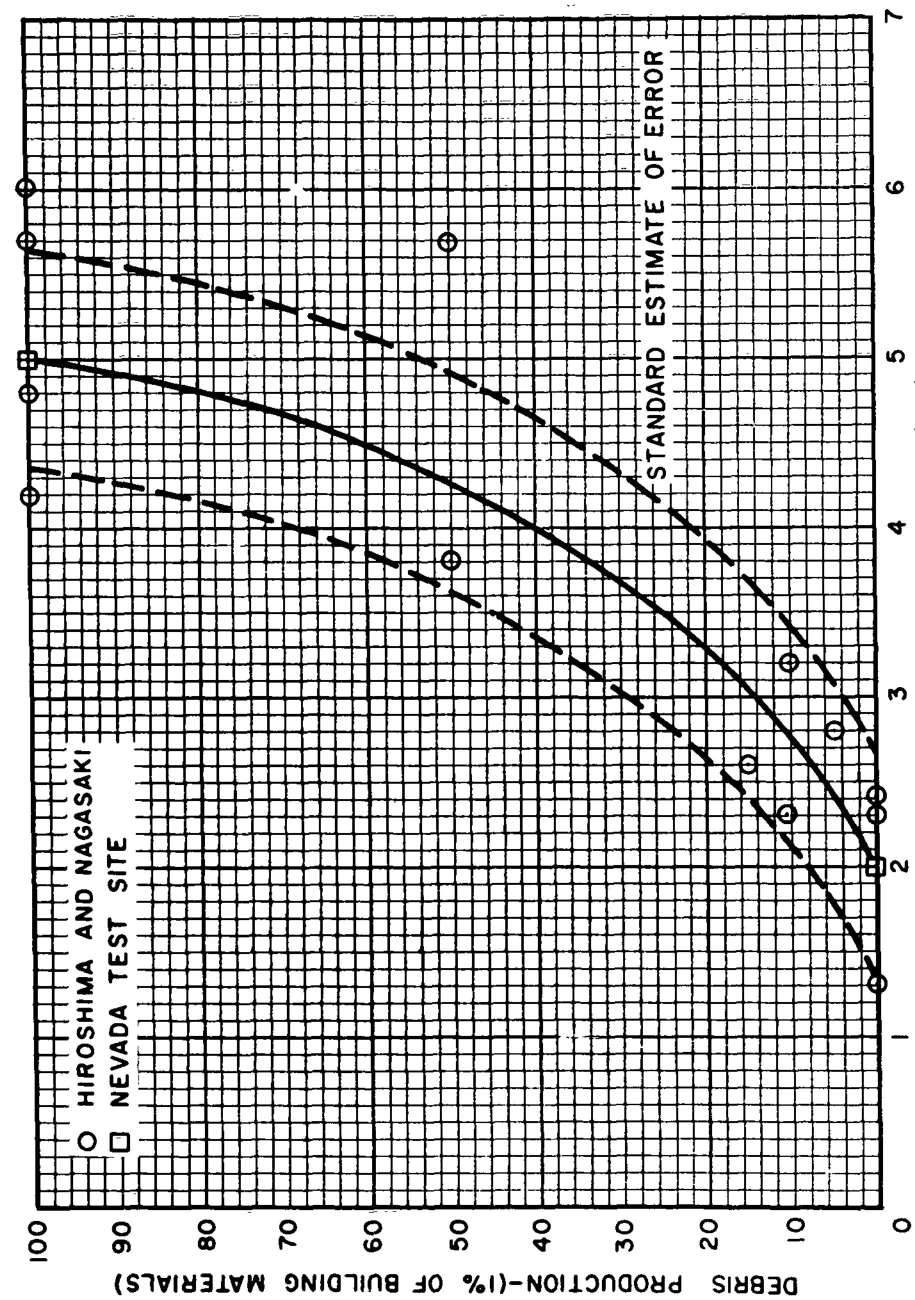

Figure 19. Debris Production vs. Overpressure; Wood Frame Buildings

This category of buildings, more than any other, is diffraction sensitive and since the overpressure at which 100 percent debris is attained will not change between megaton and kiloton yield weapons, one curve is sufficient for both yields.

Although fire will drastically alter the debris problem for this category, its effects were not considered for this report. These effects will be covered in a subsequent report.

SUMMARY CURVES OF DEBRIS PRODUCTION

In figures 20 and 21, the debris production curves described earlier are plotted together for each of the weapon yields used.

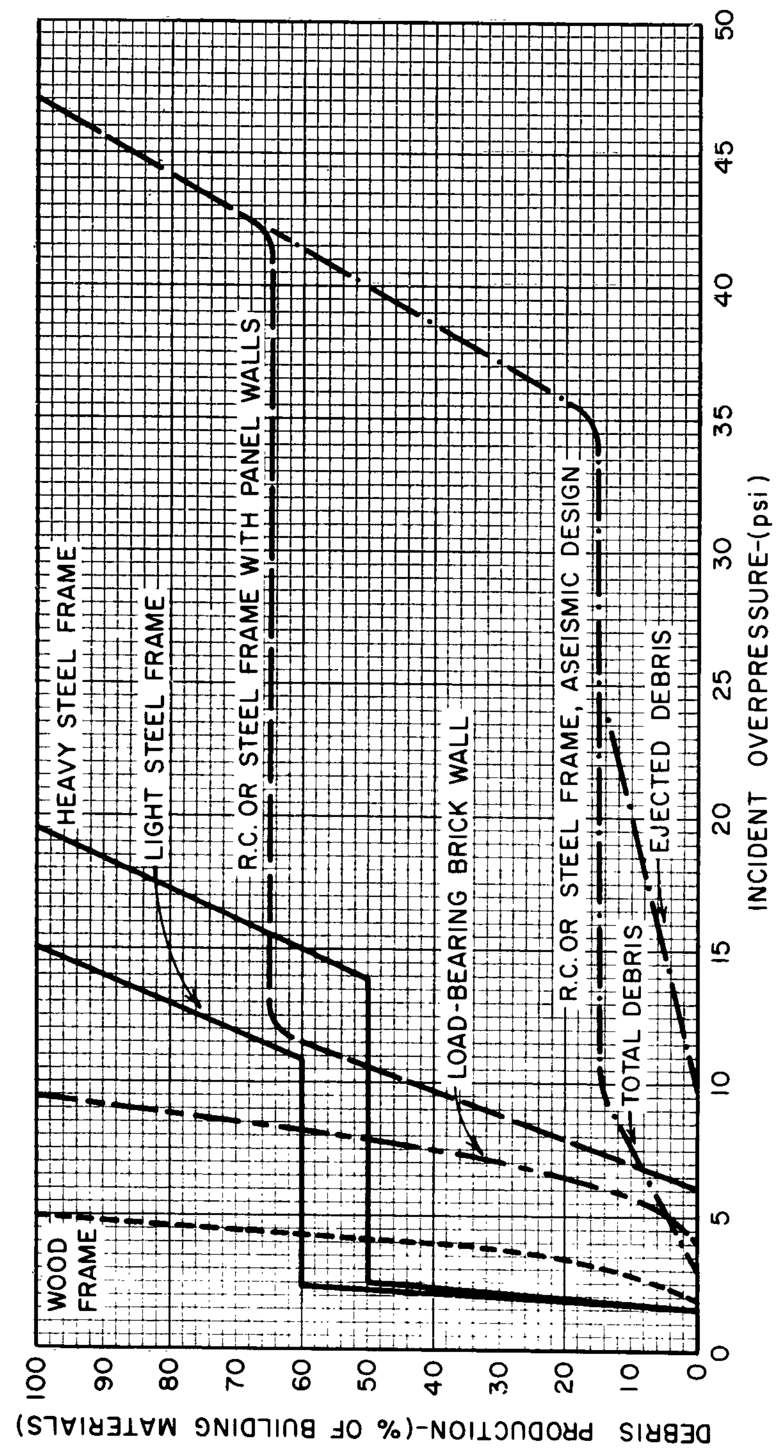

Figure 20. Debris Production vs. Overpressure; 20 Kiloton Weapon

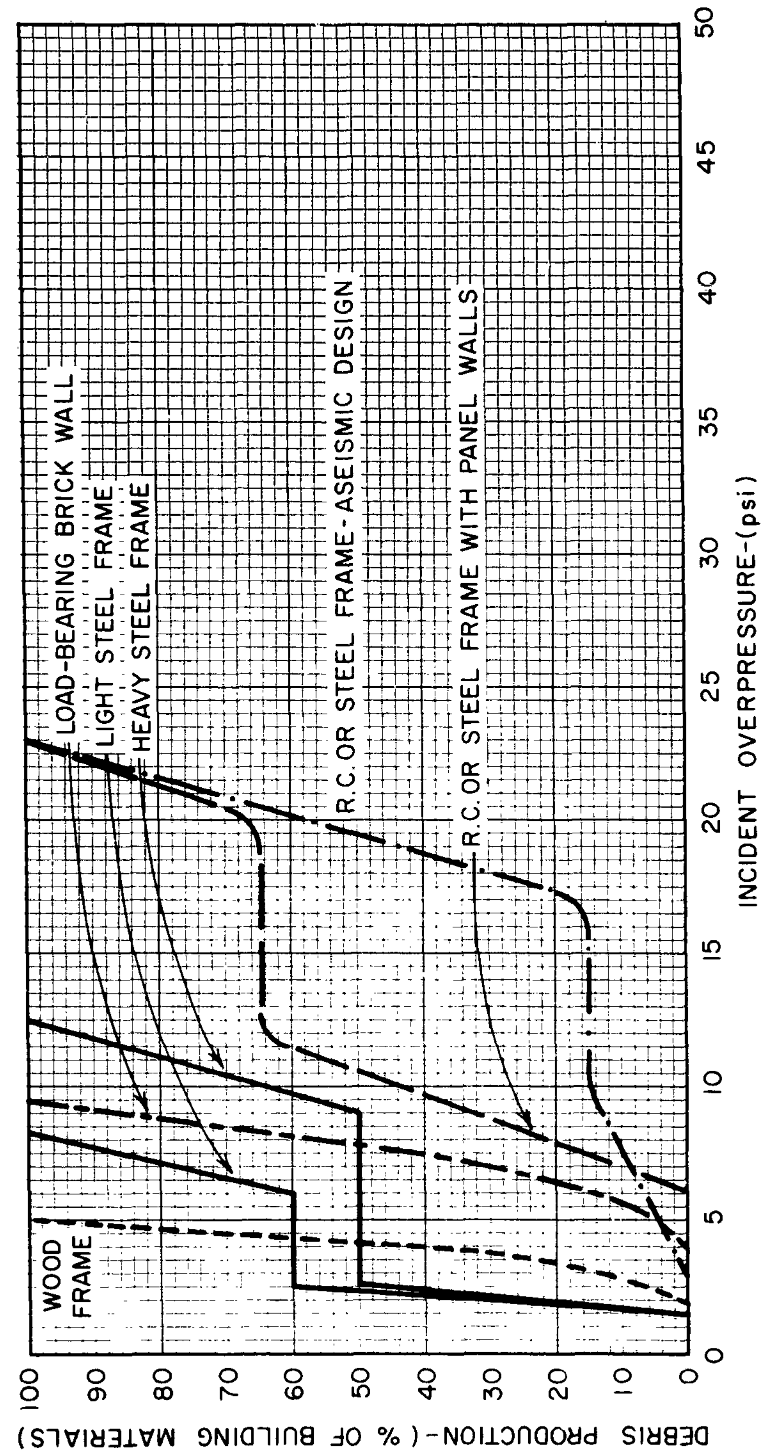

Figure 21. Debris Production vs. Overpressure; 20 Megaton Weapon

Chapter 4

RECOMMENDATIONS

The subject of this report--estimation of the quantity of air-blast-produced debris--is but one facet of the general debris problem, which includes as well determination of the quantity of debris produced by agents other than air blast (e.g., fire); estimation of types and distribution of debris; assessment of the impact of debris on mobility; and calculation of the logistics of debris removal. The relative effort to be assigned to each separate facet of the general problem, as well as the total effort on the entire problem depends on the role of such information in the basic planning functions of the Office of Civil Defense. It is in order, therefore, to examine the manner in which debris information can be used.

Most generally, the presence of debris in an area is of importance because it degrades access through or to the area. Debris within a facility in a stricken area can degrade the usefulness of the facility, and debris in areas about an otherwise undamaged resource can impede its salvage. In pre-attack planning (for postattack emergency, recovery, and reclamation operations), information on debris in an area can be used in four ways:

- As an additional factor to be considered in gross damage assessments (such as the NREC assessments) which seek gross measures of the availability of facilities or resources.

- As input for studies of the feasibility of undertaking various types of trans-attack and postattack activities, e.g., fire fighting, radiation monitoring, rescue, salvage, and repair.

- As input for studies of alternative plans for types of operations and activities that might be carried out at a regional or local level, e.g., plans for recovery of productivity; for feeding, clothing, and housing the surviving population; and for preattack positioning of equipment and personnel to carry out such functions.

- To develop techniques to be used in the postattack period which would provide local or regional managers with estimates of debris quantities and distribution.

As tabulated, these uses of debris data imply increasingly detailed analyses of urban areas and increasingly detailed requirements for information on debris. Thus, in gross damage assessments, recognition that a higher level of effort would be required to reclaim a facility or resource if debris had to be removed, e.g., from its access routes, than if there were no debris might result in changing the facility's vulnerability that had been assigned solely on the basis of structural damage considerations. For such assessments, nothing more detailed is required than broad criteria for the degradation of the ability to traverse a region as measured by gross estimates of the quantity of debris in the region.

Studies of the feasibility of undertaking various operations and of alternative plans for action would, in general, require debris information only for more-or-less homogeneous areas of urban complexes, although certain of the operations that can be studied could require such information on a scale as fine as a single, generalized city block.

Finally, the development of techniques to be used by local or regional managers in the postattack period would require analyses to be made of specific local areas and of specific city blocks.

While the last activity does require highly detailed estimates of debris production and distribution, it is clear that similar detail is not required for the other planning activities. Indeed, no purpose would be served by having more information available for carrying out one of these activities than could effectively be used.

At this point it would be well to review the information currently available and that in the process of being generated. Current information is as follows:

- URS has developed relationships between overpressure level and the amount of debris produced by air blast (as a percentage of total building material) for both kiloton- and megaton-range weapon for six classes of structures.

- IITRI has developed means for calculating the total quantity of debris that certain classes of buildings can produce if they are totally destroyed, that is, for determining the quantity of structural material contained in such buildings as a function of some measure of their size, and has studied certain aspects of the debris distribution problem.

- Dikewood Corporation has analyzed a number of cities in the United States to provide data on the distribution of building types in these cities. (The classification systems adopted by Dikewood was essentially that used by URS.)

Information in the process of being generated is as follows:

- URS is investigating the role of thermal radiation (fire) on the production and destruction of debris.

- IITRI is developing mechanistic models for the production of debris from masonry structures by blast, which should serve to refine information developed by URS. Eventually, for types of structures for which data were not available to URS, such an approach might well provide the only means for predicting debris quantities.

- IITRI is studying the logistics of debris removal.

- Dikewood Corporation is using their detailed city analyses to develop generalized or typical models of cities.

Examination of the requirements for debris information and of the foregoing tabulation of information currently available and that soon to be forthcoming reveals gaps that need be filled before the influence of structural debris on postattack emergency, recovery, and reclamation planning and operations can fully be determined. As might be expected, new information is required at a variety of levels of detail. Whenever possible, the descriptions of needed future work have been stated as recommendations for specific studies.

Debris Production

While the past and current URS and IITRI studies will generate much of the information on the quantity of debris that can be produced by a nuclear weapon attack, certain aspects of this problem have not been and are not now being considered. Therefore, it is recommended that studies with the following objectives be undertaken:

- Develop means for calculating debris quantities caused by both blast and fire for those elements of an urban complex not currently being considered, such as viaducts, bridges, trees, vehicles, and power poles.

- Develop techniques for calculating quantity of structural material as a function of some measure of structure size for those classes of structures not already considered and, for all cases, develop estimates of the accuracy of these techniques.

(The studies listed above are essentially continuations of current work at both URS and IITRI.)

- Develop means for predicting the amount of debris produced by the contents of a building (as distinct from the structural materials contained in the buildings).

- Develop measures for the type of debris produced by particular classes of structures, i.e., its weight, size, constituents, etc., as related to impairment of mobility and to the type of equipment or the logistic support needed for its removal.

- Develop criteria for the level of detail of debris quantity information required for the various pre-attack planning activities discussed previously, and develop techniques for staisfying these criteria.

Debris Distribution

To the present, debris has been assumed to be uniformly distributed over the area in which it would be produced (by IITRI in the case of complete destruction) or to be either on or off the building site (by URS for certain classes of structures). Some work has been done (by IITRI) on material distribution under simplified blast loading assumptions, but--especially for studies of particular locations or specific postattack activities--additional information is needed on more realistic urban conditions and loading assumptions. Because of the inherent complexity of the problem, it is recommended that:

- A study be made of the feasibility of conducting experimental programs to aid in the determination of the distribution of debris.

It might be noted, in this context, that studies of alterations of blast loadings within city complexes have already been conducted (by URS) and that major advances have been made in recent years in developing models of structures and structural elements that correctly respond to blast loading (by the Ballistic Research Laboratories and the Naval Civil Engineering Laboratory, among others).

As with information on debris production, the ultimate use of debris distribution information should determine how detailed the information need be. It is, therefore, recommended that:

- A study be conducted to establish criteria for the levels of detail of debris distribution information required for the various preattack planning activities discussed previously and to develop techniques for satisfying these criteria.

Debris Removal

The logistics of debris removal is currently being studied in detail by IITRI. We are not aware, however, that these studies will incorporate measures of the degradation of logistic capacity by the presence of nuclear radiation, which can be significant. It is recommended, therefore, that:

- A study be made of both the effects of fallout on debris removal capability and means for mitigating these effects.

Other Studies

In addition to the studies outlined above in the areas of debris production, distribution, and removal, other work, falling into none of these categories, is desirable. This includes studies to:

- Devise methods for revising vulnerabilities assigned to facilities (for gross damage assessments) on the basis of the degradation of mobility in contiguous areas and the general level of effort required to restore an acceptable level of mobility.

- Develop criteria for access and mobility for specific postattack activities.

- Develop simplified methods, including charts and tables, that can be used by local managers in the postattack environment to make rapid assessments of the magnitude of the local debris problem.

- Determine the impact of debris and debris removal on resource recovery.

Although it would eventually be desirable to apply all techniques developed to a large variety of cities, it is recommended first that:

- A single city be chosen and analyses of the debris problem in that city be made in depth and at every level of detail.

On the basis of this study it will be possible to:

- Develop computer programs, utilizing the Dikewood and National Fallout Shelter Survey analyses of structures in cities, to determine the magnitude of the debris problems in these cities.

Finally, an appraisal of currently available information on debris suggests that:

- The critical industries studies already carried out should be reviewed to determine whether the presence of debris in areas contiguous to such industries could alter the vulnerabilities of the industries.

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